Sustainable Tiny Home
Final Design Review

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Abigail Jones
ajone102@calpoly.edu

Sean Paddy
spaddy@calpoly.edu

Vince Bugni
vbugni@calpoly.edu

Cam Gross
cgross02@calpoly.edu

Sponsor

Sophia Smith
ssmith148@calpoly.edu

Statement of Disclaimer

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Abstract

As housing prices and environmental concerns continue to increase, many people are looking for cheaper and more sustainable ways to live. A solution to both problems is building homes with smaller footprints which incorporate renewable energy and water-reclamation systems. In addition, adding a roof pond system to the dwelling also reduces the need for heating and cooling. The roof pond system uses a water bladder on the roof which acts as a heat-sink and moveable insulation panels. This document contains the process for our final design along with results from testing the verification prototype.

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1.0 Introduction

Living in a house that is just big enough for your needs has many benefits, for the environment and for your bank account. Small houses require less material to construct, consume less energy and water when lived in, and disturb the environment less than a full-size home. When a small home uses solar power to generate its energy and collects and stores rainwater and greywater, it puts less strain on the local energy and water sources.

Under Title 24, California's new guideline for residential and commercial building projects, all new constructions are required to have a solar array. California often leads the nation on environmental matters, so it can be assumed that more states in the sunny southwest US will adopt similar guidelines in the coming years. In addition, counties across the US are allowing homeowners to add a small unit addition to their home, also known as an Accessory Dwelling Unit (ADU) without any additional zoning. Small homes with systems that promote sustainability will be increasingly popular in the coming years and selling a partially constructed home kit with these features would appeal to a wide variety of people. For example, two young homebuyers looking to finally stop renting apartments and settle down. They are looking to settle down in an economically and environmentally conscious tiny home. They have some technical know-how and probably could build their own tiny home from scratch, but they would rather pay someone to do the engineering and design for the solar and rainwater collection systems and simply receive a partially assembled product. Another type of customer is an existing homeowner who is looking to add a new ADU to their home or add solar and rainwater collection to their existing ADU. Additionally, the mechanical systems could be applied to emergency housing and facilities in less developed countries. The rainwater collection system could be used to provide water for the bathrooms and showers where there is little drinking water in the first place. These systems can also be applied to dwellings in very remote off-grid areas, where no utility can reach.

The original intent of this project was to design a tiny home along with a solar panel and rainwater collection system. However, with unexpected circumstances half-way through the project, the budget fell short, and a full-scale architectural design was no longer possible. The team continued with the original design intent but on a smaller, more manageable model. This smaller design still allowed for proper testing in order to verify that a full-scale model is possible and can be similarly designed. In the original full-scale model, the energy from the solar panels was designed to be stored in a system of batteries, so it could be used when the sun is not in the sky or is blocked by clouds. By packaging the rainwater and solar systems together, a person can easily transform their existing tiny home or ADU to be entirely off-grid, depending on location. The specific starting goal of this team was to design and build these two systems but go beyond this by seamlessly integrating the systems into a tiny home.

At the start of this project, our sponsor, Sophie Smith, was a fifth-year architecture student working on her senior thesis. In the past she has converted two full-size vans into habitable spaces in the past three years, which she lives in full-time. The vans she has built have running water, solar panels, and heating. She originally chose to create a full-scale dwelling for her thesis and was looking for an engineering team to handle the mechanical subsystems of the home. That's where we came in: our team is comprised of four mechanical engineers, all sharing similar views on sustainability and engineering ethics. Some of us have backgrounds in solar power, some of us in construction, but we all share a deep passion for the outdoors. Together, we designed a model home for a society where home prices are astronomically increasing and human-caused damage to the natural environment is reaching uncomfortable levels.

In the following report, the full-scale model was kept in mind while performing design ideas and building. The final product was a 10% scaled model of a full-scale tiny home without the solar or rainwater systems. It was determined that these systems were the least important to the projects verification and therefore, were left out. In our research, we found that the greatest way to make a tiny home more sustainable was to design better heating and cooling systems.

2.0 Background

A tiny home can present a lot of opportunities in a small footprint. As there is no set, "correct" way to build a tiny home, the designer and client have free reign over nearly aspect of the home. These aspects include decisions on the size, layout, capacity, livability, transportability, cost, and environmental impact of the home, to name just a few. In order to understand the factors behind these decisions, we conducted background research into the world of tiny homes. We focused on two lanes of research: who tiny home buyers are, and what energy systems could prove useful in a tiny home setting. When combined, these two lanes gave us a better idea of what is possible and what is desirable when moving forward with this project.

2.1 Customer Observations, Needs and Wants

Tiny homes have a smaller environmental impact compared to traditional homes; they use 93% less energy, emit 86% less greenhouse gases, and have a 56% smaller ecological footprint. 85% of tiny homes operate at above-average energy efficiency. These environmental factors all contribute to a growing tiny home market, which is steadily rising about 7% per year [1].

Tiny home buyers are far more likely than traditional homebuyers to own their home, likely due to the low cost and personalization of tiny homes. They also have less credit card debt and more savings than the average American. This means they are more likely to be financially independent and stable [2].

Solar energy is one potential way to source energy for a tiny home. In order to provide enough power for two people, about 2kW of power is necessary per day [3]. This can be produced with eight 250-W panels at about 4.4 sq feet each. The state of California gives homeowners a 30% tax credit for solar systems, however, it may be difficult to capitalize on this as a team of college students.

In order to store the energy from the panels, the most common method is a battery bank. Lithium-ion batteries are the most efficient existing battery option, but they are also the most expensive. Used electric car batteries have been gaining traction as a potential energy storage solution, however, they are not cost efficient and thus did not make sense for our initial application. The solar energy capture system was originally designed to fully fit on top of the full-scale tiny home.

Rainwater collection is a potential utilities solution for a tiny home. From a permitting standpoint, collected rainwater and its usage falls under the scope of greywater. The typical definition of greywater is lightly used water from bathroom sinks, showers, bathtubs, and washing machines. A permit is required if greywater is stored in a tank or if there is a pump used to transport the water [4]. No permit is required if the greywater is used continuously as it is collected, but it is challenging to design a useful greywater system with no storage abilities [5]. Another potential use case of greywater is reuse, as greywater can be reused with appropriate filtration. Water can be recycled using a wetland filtration system, but this requires consistent flow. The original full-scale tiny home would have needed to use a non-natural system because there will be long periods of no rainfall.

One of the biggest things our team learned during research was that around 50% of energy used in a home is lost due to the heating, ventilation, and air conditioning (HVAC) systems [26]. All other energy-using systems such as refrigeration, water heating, water pumping, lights, etc. Create the other half of the energy used. There are no statistics about overall energy consumption in a tiny home, but we estimated the statistics to hold true by calculating the energy consumption of a tiny home. A popular way of heating and cooling tiny homes is with space heaters and window-mounted air conditioners. Each of these units draw 1000-1500 Watts, whereas the next biggest energy consumers would likely be a water heater at about 1000W (which is run inconsistently) or a fridge at about 200 W. This suggested to us that by innovating in the HVAC systems of a tiny home, we could make the biggest reduction in energy usage.

The state of California encourages the construction of ADU's in order to decrease the housing crisis. The plans for new ADU construction can be submitted with the plans for new main house construction, meaning that permitting applicable for the main building automatically applies for the ADU. There is no requirement for distance between main building and ADU, but the ADU cannot be more than 25% the size of the main unit. Furthermore, there are no environmental impact fees if the ADU is less than 750 square feet in size [6].

The Living Building Challenge represented a good opportunity for achievement within the initial scope of this project. It is effectively a very high standard of "green" building certification. In order to qualify, a building must treat all stormwater on site without chemicals, and no potable water can be used for non-potable uses. Grey and blackwater must be recycled or filtered and handled onsite. Blackwater is the water from toilets and kitchen sinks. Blackwater can be handled by using a composting toilet for solid waste, while liquid can be treated externally. The building must generate all its own energy. As far as the building materials, 50% of wood product must be FSC certified, salvaged, or harvested on site, while 20% of the overall materials must come from 500km or closer. These materials cannot be on the "Red List," which specifies materials that are toxic or cause excessive environmental harm. Finally, almost all (95%+) of construction waste must be recycled [7]. Unfortunately, due to the change of sponsor and budget circumstances within our project, it was no longer possible to reach for this certification.

2.2 Existing Designs and Patents

Many innovative sustainable tiny homes already exist, and each one is very different. Some are built of clay, and which need constant upkeep. Others are made of reclaimed wood or bamboo. It seems the attraction to tiny homes is the small amount of electricity they use which leads them to be popular for off-the-grid living. Many of these homes have different devices that make them energy efficient, such as high windows for ventilation, overhangs, grey water treatment on site, old Tesla batteries to store power, and solar ovens. Some of these devices can be found in Table 1.

Table 1. Existing Tiny Home Designs and Mechanical Devices for Sustainability

Home Title and Devices Included	**Photo Demonstration**
Off-the-Grid Desert Living in a Tiny Earthen Home - Clay/earthen housing materials - Clean fireplace - Uses heat from fireplace exhaust - High windows for ventilation	 Langston, Bryce. "Off-The-Grid Desert Living in a Tiny Earthen Home & Permaculture Community." *YouTube*, Living Big in a Tiny House, 15 Nov. 2019, www.youtube.com/watch?v=QDXPIM5dxLw. [8]
Dwell Tiny Home in Seattle - Carbon negative bamboo - Overhangs - Flat roof for solar	 Pogue, Andrew. "This Solar-Powered Prefab in Seattle Raises the Bar for Sustainability." *Dwell*, Lucy Wang, 6 Mar. 2019, www.dwell.com/article/solar-studio-wittman-estes-9b3cf13b-d204a241. [9]
Off-the-Grid Tiny Homestead - Grey water treatment - Garden - Clay pot watering technique - Recycled Tesla batteries	 Tiny Home Tours. "The Ultimate Off The Grid Tiny House Homestead ~ Thriving In The Arizona Desert!" *YouTube*, 3 June 2018, www.youtube.com/watch?v=y-9pxpulqWc. [10]

Table 1. Continued

Dwell Tiny Home in the Desert - Radiant heating and cooling - Passive solar design	 Hayward, Mac. “A Writer’s Prefab Retreat Sits Lightly Upon the Land in Joshua Tree.” *Dwell*, Lucy Wang, 27 Nov. 2019, www.dwell.com/article/a-writers-prefab-retreat-sits-lightly-upon-the-land-in-joshua-tree-aeb86a7d. [11]
Wind Turbine Tiny Home Wind turbine designs	 “7 Best Home Wind Turbines.” *Tiny House Huge Ideas*, tinyhousehugeideas.com/best-wind-turbine-reviews/. [12]
Alternative Energy Sources - Solar oven - Wind energy	 Griswold, Kent. “Alternative and Renewable Energy Resources for Tiny Houses.” *Tiny House Blog*, 29 Jan. 2016, tinyhouseblog.com/tiny-house/alternative-and-renewable-energy-resources-for-tiny-houses/. [13]

The world’s reliance on finite fossil fuels has been facing a change over the past few decades, as people realize how they pollute the atmosphere and contribute to global warming. There has been an increased effort over that time period to discover alternative solutions to this global energy problem. Many patents have been developed as a result of research in the field of renewable energies and how they can be applied by everyday homeowners. While solar power used to be nothing more than theory, today it is common to see the roofs of residential homes with solar panel arrangements mounted to them, especially in climates featuring lots of sunshine. It's clear that as research in these fields increase, the accessibility to these technologies does as well. Table 2 provides a few relevant patents for this project.

Table 2. Possible Relevant Patents.

Patent Name	Patent Number	Key Characteristics
Solar house [14]	CN102635159B	• Heat insulating walls • South-facing sunroom • System contained in house basement
A solar electricity-generation, energy-accumulation water-heating device [15]	CN201084872Y	• Energy storage with water heating • Utilizes far infrared part of solar energy
Solar energy household system [16]	CN203178809U	• Sunlight tracking system • Able to support shower, refrigerator, A/C unit, radiator, & more
Glass house having a rainwater collection and irrigation system [17]	GB2455605A	• Roof mounted rainwater collection and distribution system • Enables inhabitants to lower carbon footprint
Intelligent and efficient off-grid solar home energy system and method thereof [18]	US9819219B2	• The system generates, stores, and delivers the solar energy in an efficient manner • Home control unit • Batteries arranged for maximum power storage

2.3 Relevant Technical Literature

In recent times, environmentally friendly approaches to old practices are becoming more and more necessary. Since the start of the production of devices that convert solar energy into electricity, it has been possible to produce electricity and send it up the power grid, and then have savings on your electric bill. Tiny homes are often built and connected to the grid so that they do not have to have battery storage [19]. However, in this situation, the tiny homes are still using non-renewable energy from the power grid at night or during cloudy days. This is why 100% solar reliability is necessary and applicable for some tiny homes [20]. To increase energy savings, especially during the night for heating, the building must be insulated well. This can be done a number of ways but a recent, very earth friendly way, is to have a rooftop garden of which is sustainable through many different aspects such as, water savings, energy use, waste management, emissions, and farmland preservation [21]. There are many different ways to save water, of which could be applied to the rooftop gardening. One way that has been established is to grow plants in a container were the water cannot, or slowly leaks into the surrounding soil to keep water around the plant as long as possible and wastes water as least as possible [1].

Not only do plants provide food, but they can also clean water as well. Grey water can be filtered and reused for plant watering using plants adaptable to "dirty" water. Using a pump system that resembles one used in *Grey Water Treatment for Reuse,* the water can be converted into clean enough water to feed the garden [22]. It is important to reuse and recycle as much as possible, and this applies to the envelope as well. To have a truly earth friendly home, the building materials must be affordable, bio-based, and earth-friendly. These materials include materials that are abundant in nature, less toxic, economically affordable, and versatile [23].

2.4 List of Industry Codes, Standards and Regulations

According to the 2019 revision to California's Energy Commissions Building Energy Efficiency Standards, all low-rise residential structures must have photovoltaic systems with electrical output greater or equal to the dwellings' annual energy usage [24]. As the dwelling in this project was planned to be off grid, it was not a problem to meet this regulation.

For a full-scale design, the photovoltaic array and energy storage system need to be fully designed prior to the submission of permits to the county. This would include a detailed description of the system and its components, proper selection of conductors, controllers, and inverters, and detailed wiring design. A proper site analysis would also be required, with location of other buildings and obstacles and proposed location for solar array, inverters, and batteries. The built system must also be inspected by a county official before it is approved for use.

San Luis Obispo receives an average of 21.6 inches of rainfall per year [25]. This rainwater runs off the roof and can be stored in a collection device with no permitting required, provided there is no use of electronic equipment in the collection system. The rainwater can then be used for any type of irrigation, significantly decreasing the unnecessary use of clean potable water. Additionally, graywater produced by bathroom sinks and showers can also be reused. This also requires a permit from the county for a full-scale tiny home, after the system has been designed.

3.0 Objectives

The objective for this project was to design an alternative living space that specializes in its efficient and creative use of natural resources. The outcome of this project, even though a model, reflected its user, where the shelter is an extension of the customer's personality and lifestyle.

3.1 Problem Statement, Customer Needs and Wants, and Boundary Diagram

Problem Statement: The independent and universally conscious homebuyer needs the option to purchase an inspiring, low-footprint and self-sustaining homebase to reduce the financial and environmental costs of current home ownership.

Originally, the customer had envisioned a structure of about 200 to 300 square feet. It was important that the scaled down model represent a building with systems of high reliability, where the owner could leave it untouched for a year and return to find it functioning as if they had never left. In Figure 1, the full-scale home and systems are displayed and were considered in the preliminary design process.

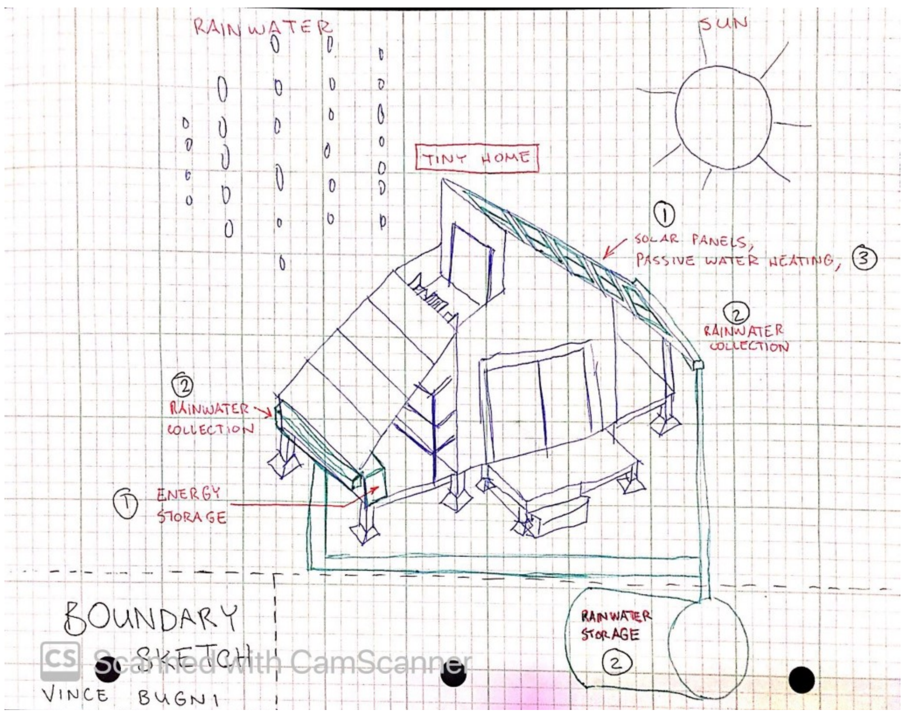


Figure 1. Boundary Diagram

In Figure 1, the boundary diagram shows how outside systems affect the systems being designed and how each of them works simultaneously together. Even though Figure 1 is based off of a full-scale design larger than a 15’ by 10’ later described, there is only a limited amount of space for all of the subsystems to function.

3.2 Engineering Specifications

Specifications help determine the amount of material and processes that need to be used to satisfy the consumer. In order to gauge the success of the building’s systems and the overall livability of the house, a number of quantifiable specifications for the building have been set. The specifications developed for the full-scale model can be found in the Table 3 and in the Quality Function Deployment (QFD) in Appendix A. The QFD process was developed on the basic outline of key deliverables, which can be found in Section 4.1. After the outline was made, smaller tasks were added to develop the processes of completing these major tasks.

Table 3. Engineering Specifications (Full-Scale)

Specification Number	Specification Description	Specification Target	Tolerance	Risk	Compliance
1	Total Energy Storage	5000 kWh	±200 kWh	High	Analysis, Test
2	Water Pressure	40 psi	Minimum	Medium	Test
3	Total Water Flow Rate	6gpm	Minimum	Medium	Test
4	Window U-Factor (Insulation)	.3	±.05	Low	Inspection
5	Cost of Materials	$10,000	±$5000	High	Analysis
6	Weight of Solar Subsystem	100 lbs	±20 lbs	Medium	Inspection, Test
7	Size of Subsystem	125 cubic feet	±10 cubic feet	Low	Inspection, Test
8	Daily Energy Output	5kWh per day	± .1 kWh	Medium	Analysis, Test
9	Average Temperature inside home	72°F	±5°F	Low	Test

All of the specifications have a target value and a tolerance. If a specification was found to lie within the tolerance, it was deemed acceptable. The risk of the specification gives an indication of the difficulty of meeting that target tolerance. The compliance shows how the specification will be tested. If all specifications were met, the home will have water and energy systems that are comparable to that of an average full-sized house, while being small, transportable, and cost-effective.

The original specifications included factors that were established to determine the home's livability. These included the total energy storage and daily energy output, the water flow rate and storage capacity, the water pressure, and the window insulation U-factor. As the project progressed and the team experienced unforeseen circumstances, these specifications were adjusted (Table 4) to fit within a more reasonable scope of work with respect to the available funding and resources.

Table 4. Model Engineering Specifications

Specification Number	Specification Description	Specification Target	Tolerance	Risk	Compliance
1	Inside Temperature	72°F	±5°F	Low	Test, Analysis
2	Gear System	5 runs working smoothly	1 run	Medium	Test
3	Stability of roof pond	No movement with 150 lbs.	-	High	Test

The focus of our engineering specifications was shifted to prioritize the viability of the roof pond system as a proof of concept. In Table 4, the specifications used to validate and reflect our smaller model are shown.

4.0 Concept Design

The final concept, for both full-scale and the model, features a roof pond over the main structure. There is an additional awning that is attached to the side of the structure along the long end. The roof pond and awning are slightly sloped with the awning rising to a higher elevation, thus allowing the surface of the roof to face further south. The awning has solar panels mounted to it, and the entire roof surface was designed to capture rainwater. A detailed CAD drawing, prototype model, and justification of the final design can be seen in this section.

4.1 Ideation Process

The ideation process was a critical step in ensuring that the final design was well thought out. A good ideation phase left the team with a wide range of ideas to develop and an accurate picture of each idea's merits. This confirmed that the team had thought through all potential design solutions and had a justifiable final concept. Even though the ideation process was completed in terms of a full-scale design, all ideas were applicable to the final prototype as well.

For the first step in the ideation phase, we undertook a process known as functional decomposition. Functional decomposition is a method of analysis that seeks to identify every critical function and sub-function present in the design. To do this, we listed every major functional requirement of the home. Then, we broke these down into their critical subfunctions and discussed each, leaving us with a better understanding of the design challenge.

In order to develop ideas for the numerous functions of the home, each team member led a different ideation session for selected topics. Examples include a brainwalk on how to collect rainwater and a braindump on energy generation methods. During these sessions, members were encouraged to think as freely and creatively as possible, taking a ‘no bad ideas’ mentality.

After ideation, we were left with a range of potential design solutions. This created a need to narrow our choices down using relevant criteria. For each function, we created a list of requirements, and judged each concept on said requirements. This lent itself to the creation of Pugh Matrices, wherein each concept was ranked numerically against a datum for each requirement. Once completed, these matrices painted a clear picture of the performance of each concept, as well as where each’s strengths and weaknesses lie. The Pugh matrices can be found in Appendix B. From the Pugh matrices, the best performing concepts were selected for further development.

4.2 Selection Process

Following the creation of Pugh matrices for the necessary functions, a morphological matrix was created to synthesize the best combinations of ideas. The resulting full-system concepts can be seen in Figure 2.

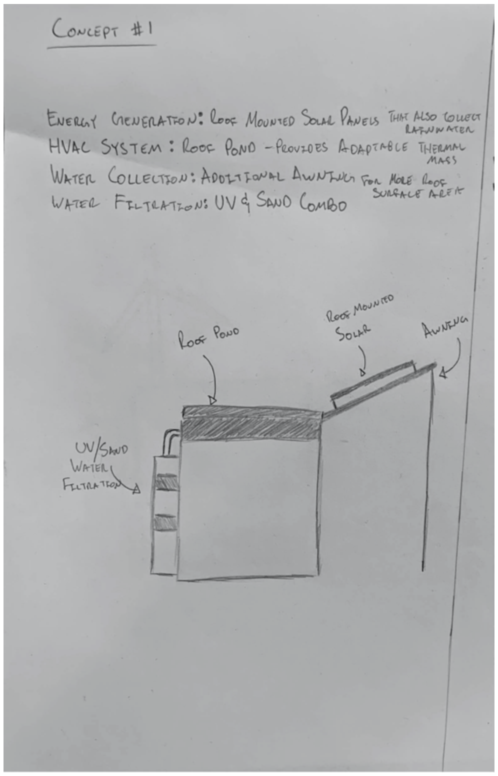


Figure 2a. Concept 1 Sketch.

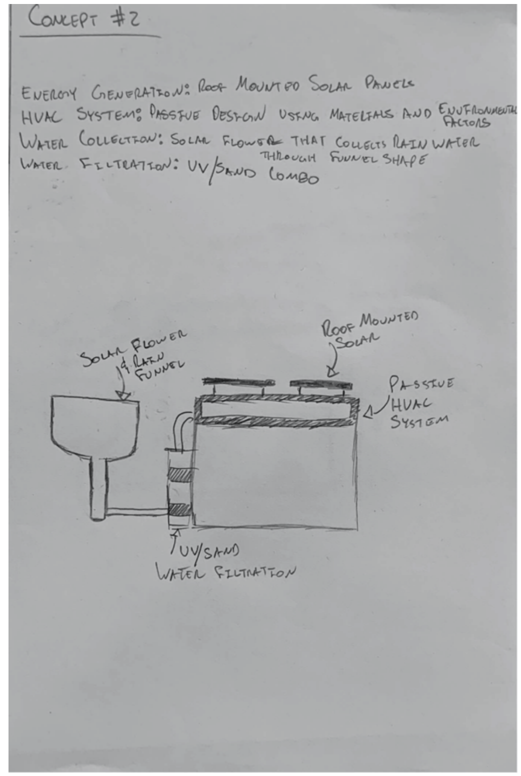


Figure 2b. Concept 2 Sketch

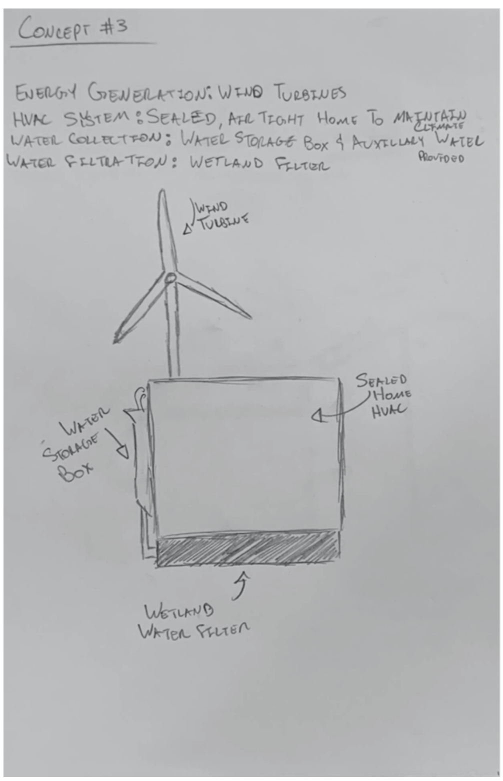


Figure 2c. Concept 3 Sketch

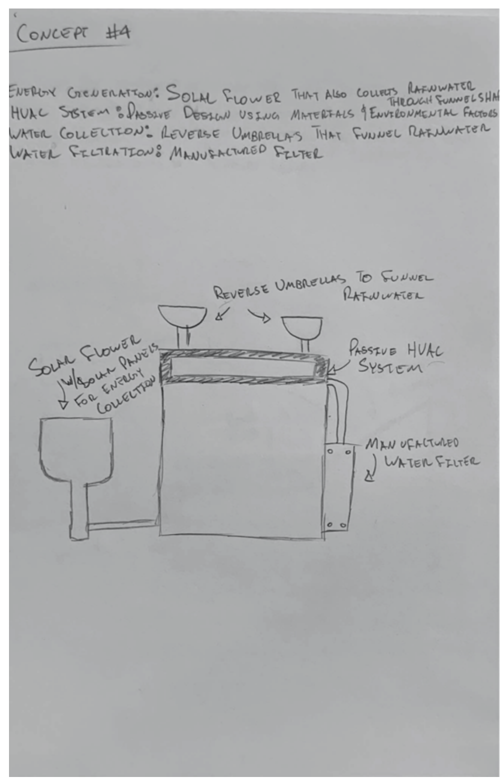


Figure 2d. Concept 4 Sketch

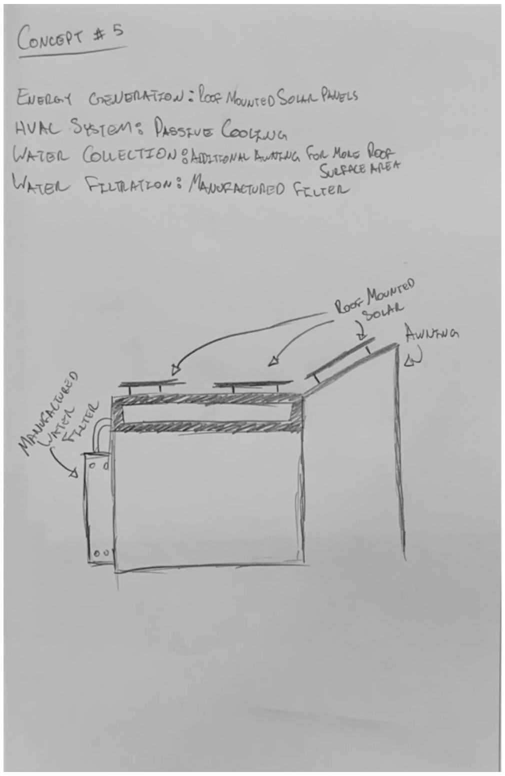


Figure 2e. Concept 5 Sketch

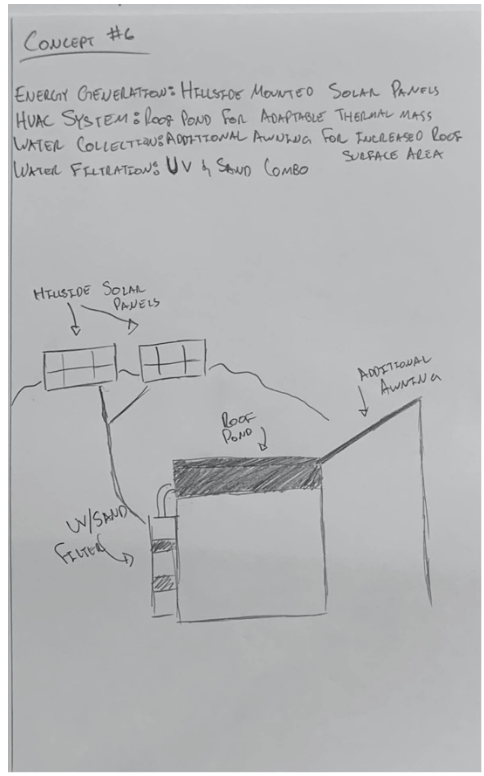


Figure 2f. Concept 6 Sketch

Solar panels were the most common method to generate energy and can be observed in five out of six concepts. The other option for generating energy was through wind turbines. Solar was the preferred method for generating electricity in the building for its overall consistency and economic viability compared to harnessing wind energy. For the building's HVAC system, a roof pond was incorporated in two of the concepts, a passive system involving careful architectural design and material selection was used for three concepts, and a tightly sealed living space was used for one concept. Despite the increased complexity and cost of utilizing a roof pond system for the structure compared to other options, the roof pond was selected as the preferred HVAC system for the structure due to its unique and creative attributes. For the purpose of collecting rainwater for the full-scale building, an additional awning attached to the side of the building was preferred and can be seen in three of the six concept sketches. The other methods of using solar flowers and reverse umbrellas were determined to require too much development and resources to be economically and logistically viable for the scope of the original full-scale project. In addition to its simplicity and cost-effective attributes, the awning increases the surface area of the roof, which in turn provides more creativity in integrating the roof pool and solar panel subsystems together. A combined UV light and sand filtration system was selected as the best method to filter collected rainwater. This was chosen over the other options of a manufactured filter and a wetland filter due to its reliability, high user safety rating, and economic practicality. As seen in the Weighted Decision Matrix in Appendix C, the winning concept from this ideation process was Concept 1 (Figure 2a).

4.3 Selected Concept

The full-scale selected design concept met and exceeded all other designs when comparing them based on the criteria this project. The design rated especially high in the areas of cost, energy output, sustainability, innovation, and creativity. The temperature inside the home is kept constant using the high heat capacity of water; lowering the energy needed to heat and cool the home compared to other concepts. On top of the full-scale tiny home would sit three to four large jugs of water. These jugs would completely cover the living space below the roof, which is also true for the built model. This ensures that no area of the roof will be exposed to sun, and therefore, unevenly heat or cool that area below the ceiling. On top of these water containers lies insulation panels. These panels keep the sun's heat radiation out when it is hot outside, and in when it is cold. For example, if the outside temperature during the day reads 90 degrees Fahrenheit, then the panels for that day would be covered so that the water sitting on top of the roof would not absorb heat. That night, the panels would be removed so that the water could release as much heat as possible to keep the house cool the following day. This method would be reversed if it was cold during the day; the water would heat during the day keeping the house warm throughout the day and night. Figure 3 shows this full-scale roof concept design visually. On the right, the insulating panels are removed to show the water containers below. On the top left, the insulating panels are shown half covering the water containers as to show how they are covered and removed.

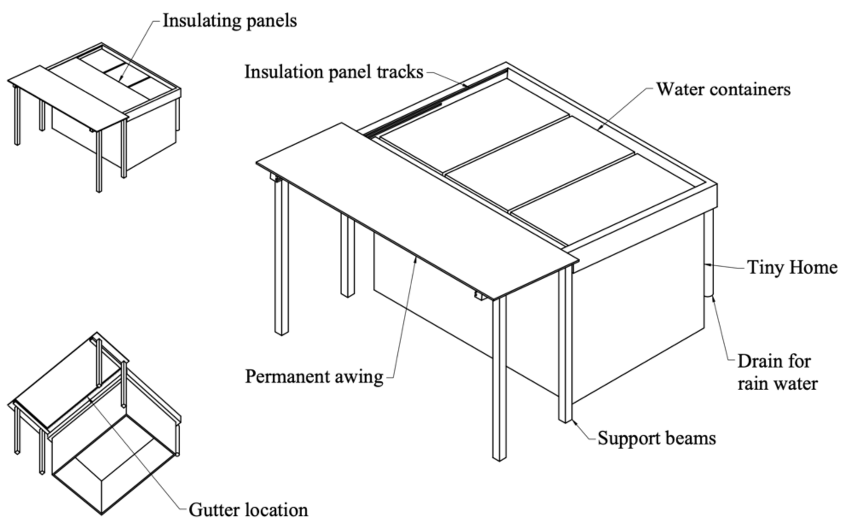


Figure 3. Fusion 360 model of roof concept design.

For the insulating panels to be removed and put on with ease, a simple mechanical system was implemented. This design was scaled down for the final prototype but is otherwise identical to the envisioned full-scale models' system. The system is powered by a hand crank; when the homeowner wants to move the panels, the homeowner turns a circular wheel, much like a wheel in a car. The wheel winds a rope and using a pulley system, which pulls the panels off of the water containers, exposing them to the sun. To move the panels on top of the water containers, the homeowner then moves the insulation panels back by turning the wheel the opposite direction and the panels are pulled back into place. In order to have a place to store the insulating panels when off of the water containers, an awning was built next to the roof (as can be seen in Figure 3). To save space and ease of mobility, the insulation is comprised of two panels that slide on top of one another. When removed from the water containers, they fit on top of each other under the awning, as can be seen in Figure 4. The awning also serves as a place to hold solar panels to power the tiny home.

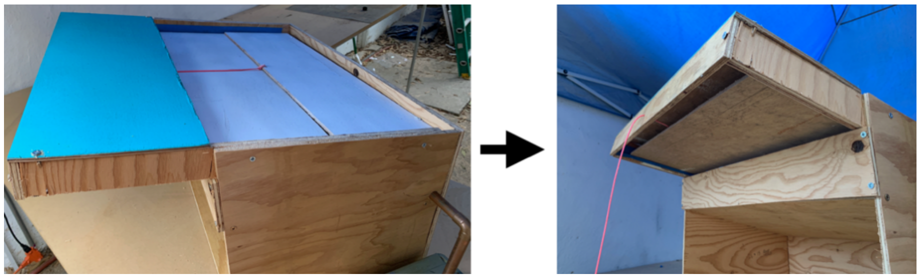


Figure 4. Panels slide from on top of water containers to under awning.

The pulley system works by attaching a rope material to the top insulation panel (the furthest from the awning). When opened by the homeowner, the top panel slides on tracks (as labeled in Figure 3) on top of the other panel. When the top panel reaches the end of the bottom panel, a lip on the top panel pulls the bottom panel with it. This was completed by having a steel rod placed on the left side of the awning (when looking at the left photo in Figure 4). The rod turns when the wheel is turned, pulling the panels with it in the way described above. The mechanical system is displayed on the outside of the home to show how all systems on the home have purpose. The awning is slightly larger than half the size of the roof since it holds the insulation panels under it. The panels slide on plastic strips to ease friction in an aesthetic, mechanically simple, and cheap way.

The water ponds should be at least 6 inches deep for effective heating and cooling in the full-scale design. For the smaller scaled model, the depth of water was proportional to the heat transfer into the volumetric space inside the tiny home. The pulley system is comprised of two pulleys to pull the panels up and down the roof. As can be seen when comparing Figure 3 to Figure 4, there are support beams in Figure 3 that are not in Figure 4. These beams were not needed as the strength of the beams, weight of the panels, and forces combined when releasing or pulling the panels was not enough to strain the structure.

4.4 Preliminary Analysis

A target value of 5kWh per day of energy generation for the full-scale home, a conservative estimate for our reduced energy needs. We calculated the size of the solar array needed to provide this amount of energy, based on a conservative estimate of 5 hours of reliable daylight per day. The result was a panel array of about 70 square feet, which is less than the minimum planned size of the full-scale awning. This means that, for the full-scale model, a full array can easily fit within the space allotted. Alternatively, the array could be grown to fill the size of the awning and thus exceed our energy generation goals.

We also calculated the weight of the roof pond in order to determine the loads seen by the structure. We were responsible for providing the ultimate loads to inform the sponsor's designs. For calculation, the roof pond was assumed to be 8" deep, as is the maximum depth of a full-scale effective roof pond. This led to a total roof load from the water of 10400 lbs., or 5.2 tons. Hand calculations for the preliminary analysis can be found in Appendix D.

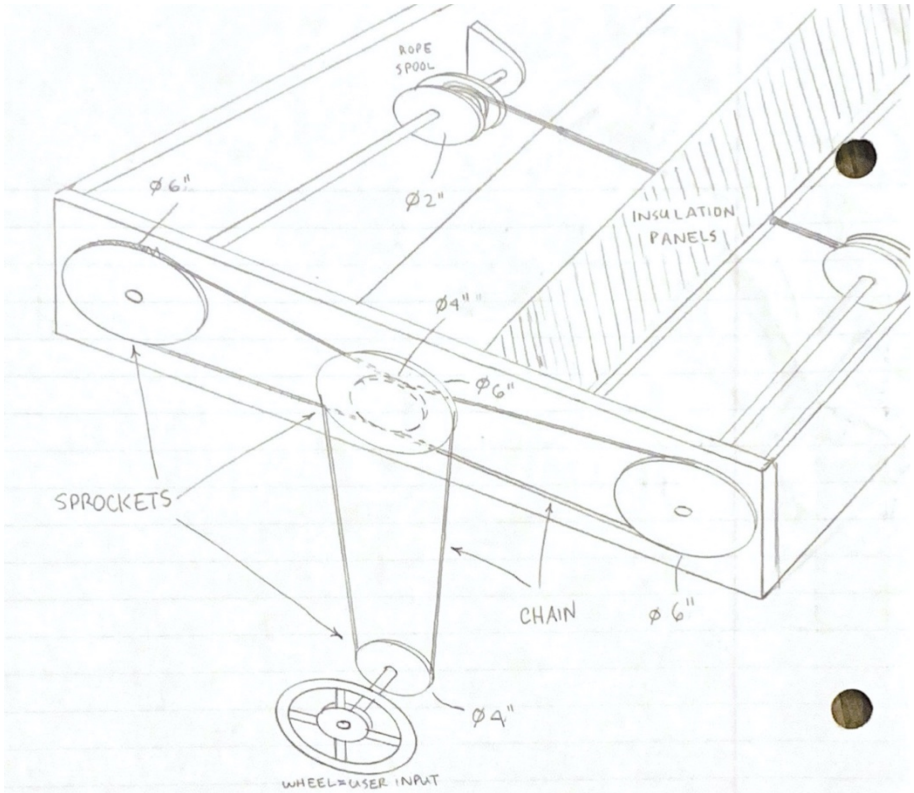


Figure 5. Initial sketch of panel movement system

Hand calculations were performed in order to find the amount of force required for the user to input to move the insulation panels. Estimating that each insulation panel will weigh 60 pounds, at most the user will have to move two panels at once, totaling to 120 pounds. Assuming an angle of 5 degrees and a coefficient of static friction of 0.2, the coefficient between dry steel and UHMW plastic, and a three-step torque reduction as shown in Figure 5, the user will only have to input 5.1 pounds of force. Hand calculations can be found in Appendix D.

4.5 Design Hazards

Prior to building and testing, careful consideration of design challenges and risks have been taken into consideration. The Design Hazard Checklist, which can be found in Appendix E, details the various risks that have been anticipated for a full-scale design. The final concept features moving parts through the sliding panels on the roof pond and the pulley system that controls it, making it important for protective paneling and warning labels to be used. Additionally, the structure of the building needed to be strong enough to support the weight of the roof pond and all its components. Similarly, the awning required a strength large enough to bear the weight of mounted solar panels and insulation panels. The structure of the building was also designed to bear loads of extreme conditions, such as a high wind or falling branches. To accomplish this, high factors of safety were used when designing the structure of the building.

5.0 Final Design

This section discusses the final design of the mechanical and structural systems for the tiny home. It also considers the safety, maintenance, repair considerations; discusses why specific parts and materials were chosen; and summarizes the cost analysis associated with the final design. It is important to note that substantial changes have been made at this point in the project regarding the scale and design feasibility of the final design.

5.1 Final Selected Design

Our final design focuses on showing the abilities of sustainability-driven design, featuring a roof-mounted pond system with actuating insulation panels for a blend of both active and passive heating and cooling, creating an adaptive climate control system for the home. The original intent of the home was to have mounted solar panels on the roof, thus allowing the home to be electrified for fully off-grid living. Additionally, a rainwater collection system using the geometry of the roof and a storage tank was strongly considered. Due to lack of funding and space to fulfill these ideas, the team chose to focus on ensuring the completion of the roof pond system. The final design is a scaled down model from what is shown in Figure 6, from a 10' by 12' tiny home, to 4' by 6'.

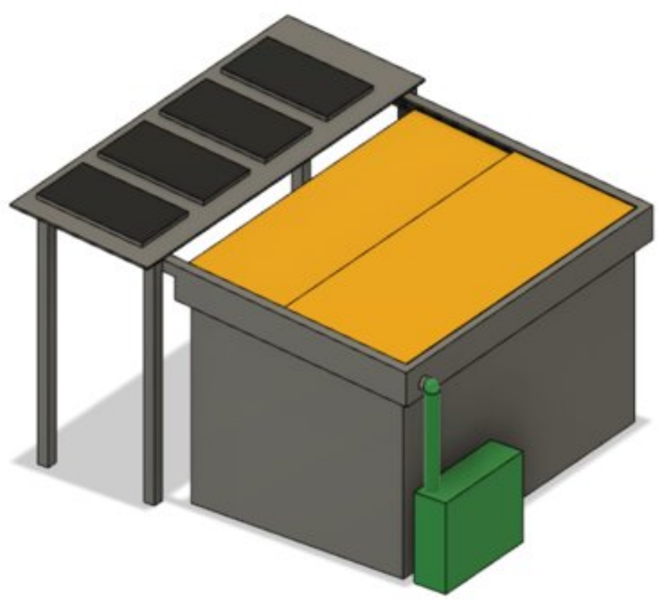


Figure 6. Fusion creation of final concept design

The full-scale final model is shown in Figure 6 to demonstrate the overall design intention. The final built project is the tiny home without the black solar panels or the green rainwater system. The home itself is a 4' by 4' cube framed out of standard 2" x 4" framing studs while the awning overhangs the door to provide home with an additional 2' in profile length. The size was chosen based on a large enough space inside the tiny home for air temperature to be similar to that of a large, tiny home with limitations due to sizing of wood and budget.

5.1.1 Full-Scale Solar Panel Assembly

Solar panels were planned be used to provide electricity to the tiny home by collecting solar energy, however, due to budget and a lack of need to test them, we decided to not include them in our verification prototype. This electricity would have been stored in batteries contained within the structure and the solar panels themselves mounted on the awning attached to the side of the building using a metal railings and z-mount brackets.

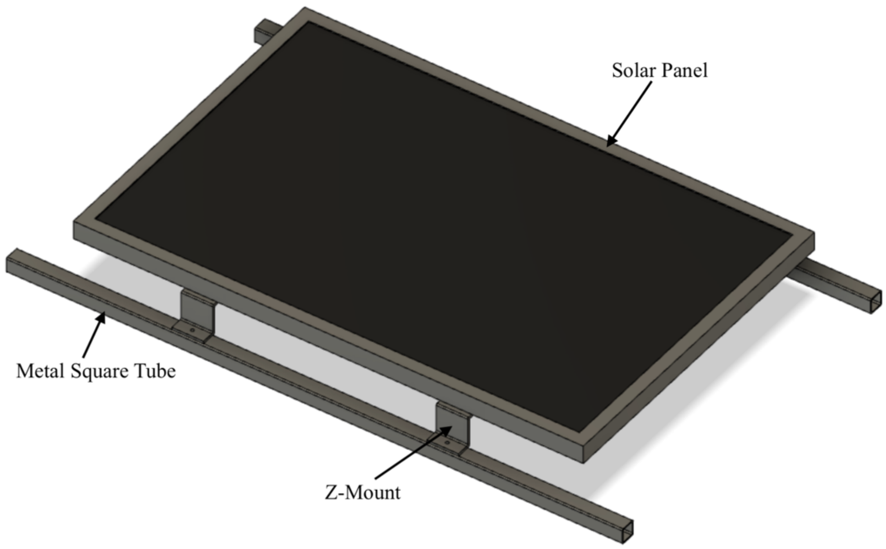


Figure 7. Solar panel assembly that attaches to awning

To understand the full-scale model, Figure 7 illustrates the solar design that would be placed on top of the full-scale awning. It would lay on top of the awning structure so that it does not affect the movement of the insulation panels.

5.1.2 Roof Pond Assembly

The roof pond structure can be broken into three separate subassemblies (pond frame, roof deck, pond cover) that connect together. The pond frame includes the framing lumber, the fasteners it requires, and the pond liner. The roof deck consists of the aluminum sheet metal that are adhered to the base of the pond frame and the roofing asphalt sealant used to prevent unwarranted leakages. The pond cover, shown in Figure 8, includes the plywood panels that frame around the pond frame, the clear polycarbonate panel, and mounting hardware.

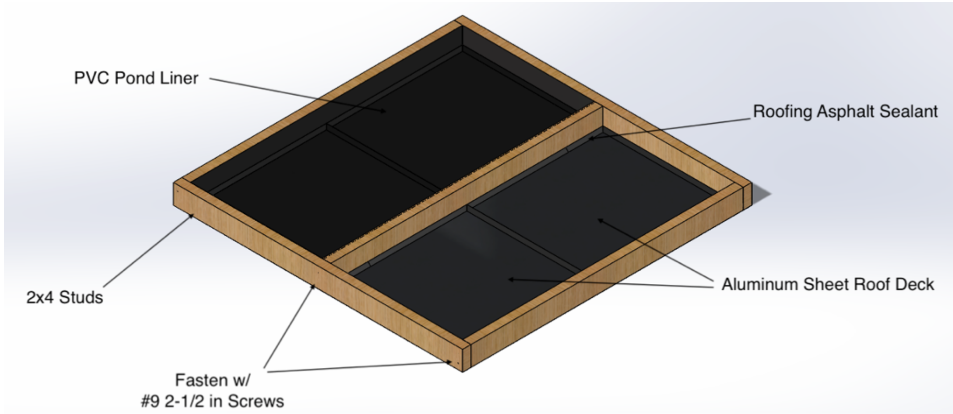


Figure 8. Roof pond water holding design with labels

The roof pond utilizes the heat capacity of water to provide adaptive heating and cooling for the tiny home. This design features a series of tightly sealed tubs filled with two to three inches of water that are placed on the roof of the home. Additionally, fully retractable insulation panels work in cooperation with the roof pond, allowing the user more control over the climate of the tiny home. The panels can be fully retracted to expose the water to more direct solar radiation. This radiation penetrates the clear polycarbonate covers (Figure 9) and heats the water. The heat is then conducted through the aluminum sheets at the base of the roof pond and through the ceiling of the tiny home.

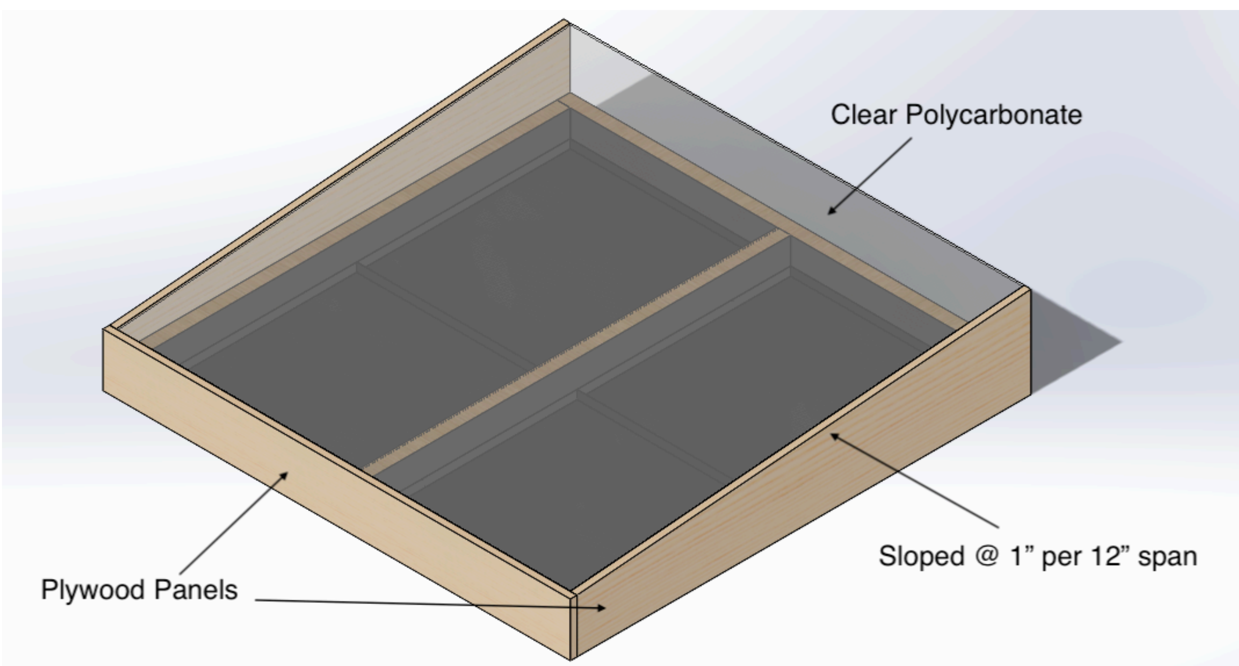


Figure 9. Outer roof pond assembly

Additionally, the insulation panels can be adjusted to cover the pond, allowing the water and home to stay at its desired temperature for a longer period of time. If the user desires the home to be cooler, the insulation panels can be left closed during sunlight hours to prevent the water in the roof pond from absorbing solar radiation, and it can further be cooled by opening the insulation panels at night.

5.1.3 Insulation Panels

The insulation panels for the roof pond rest on a track that travels the length of the roof pond assembly and continues onto the awning. A user-controlled gear and chain mechanism (Figure 10) is used to move the insulation panels between its two positions, covering the roof pond, or exposing it.

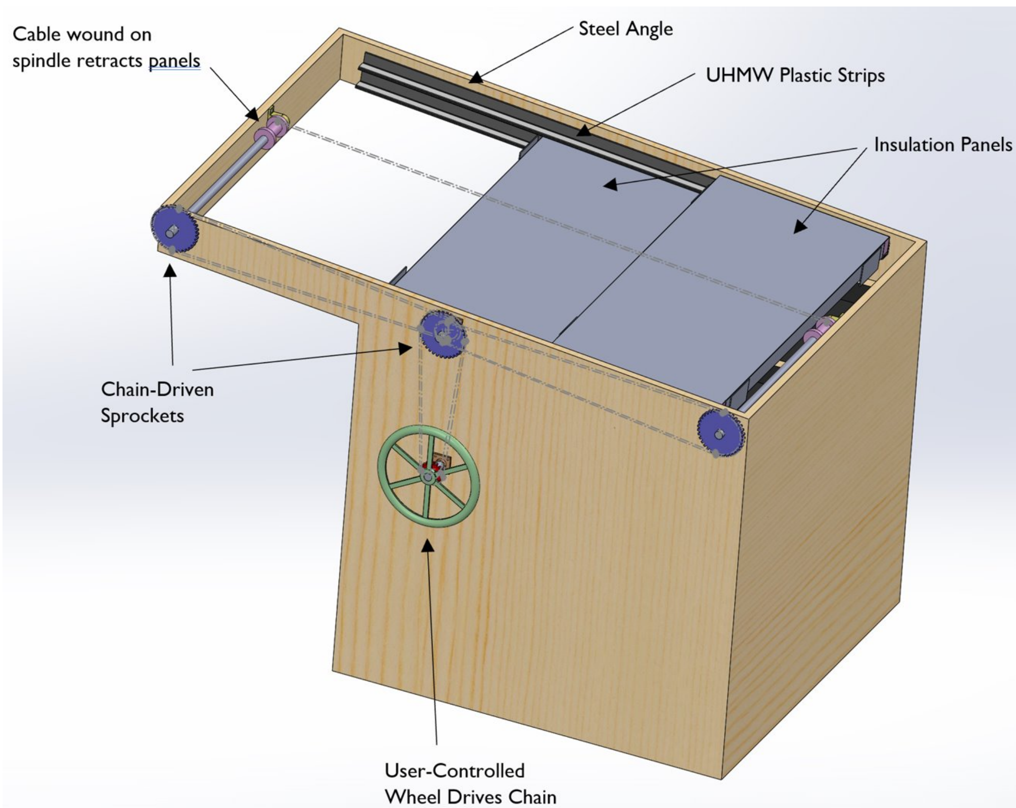


Figure 10. Insulation panels with movement control

When the insulation panels are fully retracted, the panels store into the awning and underneath the mounted solar panels. These solar panels are not shown in Figure 10 in order to show the cable wound on a spindle to retract the insulation panels. However, the solar panels would lie on top of the open space shown on the roof of the tiny home, on the upper left. In Figure 11, the insulation panels are shown after they have been moved off of the water.

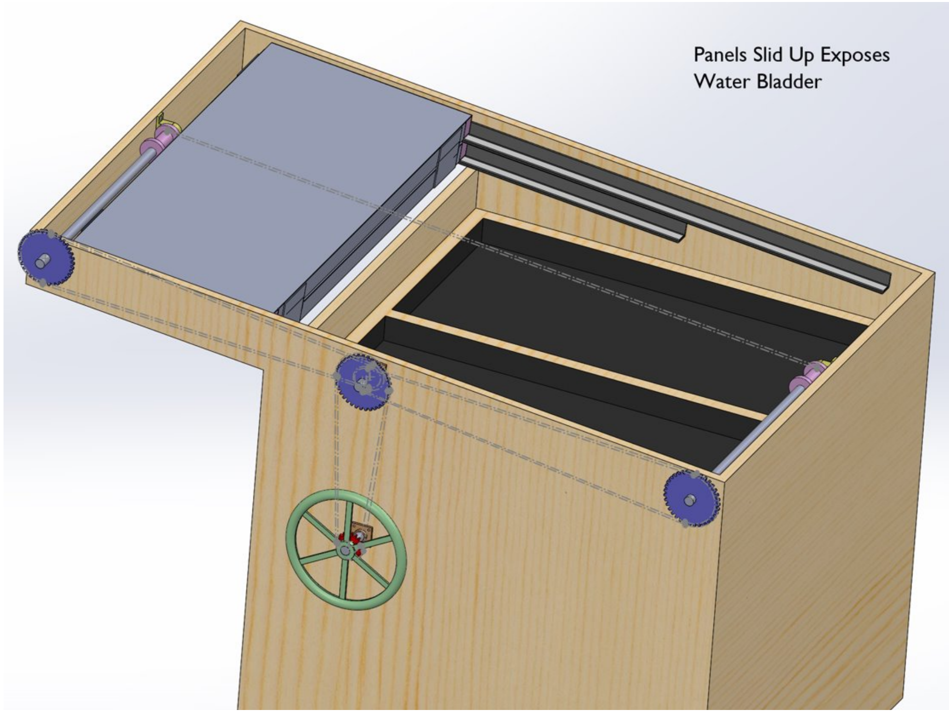


Figure 11. Insulation panels fully retracted

The insulation panels are made of polystyrene insulation and supported by steel channels. Steel catch tabs, as seen in Figure 12, were used to allow for the panels to move in unison while being retracted.

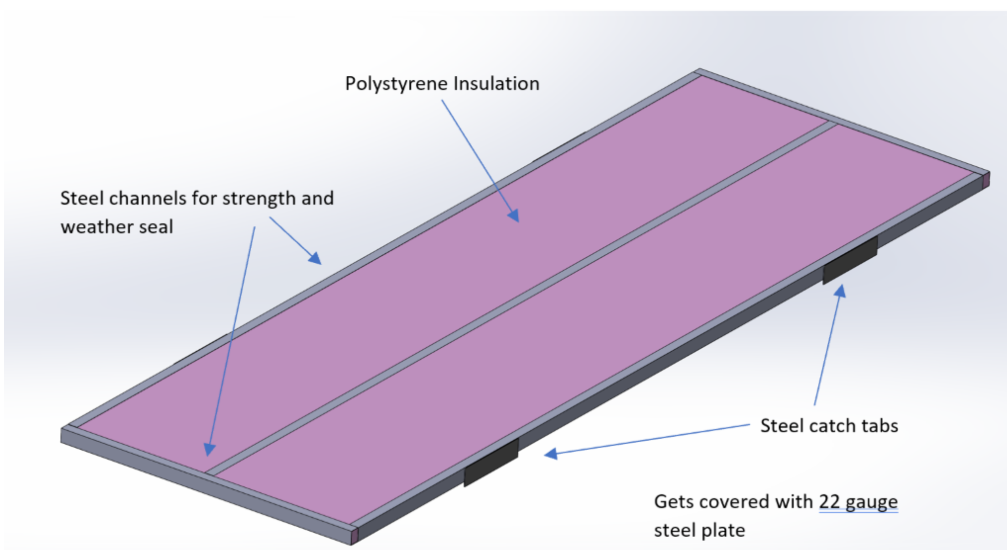


Figure 12. Insulation panels with labels

In order to test the model before building the final verification, a simplier prototype was built and shown in Figure 13.

Figure 13. Structural prototype

The structural prototype demonstrated the feasibility of the roof pond insulation panel system. Specifically, it verified that the panel movement mechanism and overall layout of the system was viable.

5.1.4 Full-Scale Rainwater Collection and Filtration System

In the full-scale model design, rainwater will be collected into and tank and subsequently filtered to provide drinking water for the tiny home. Figure 14 shows the geometry and proposed placement of the system.

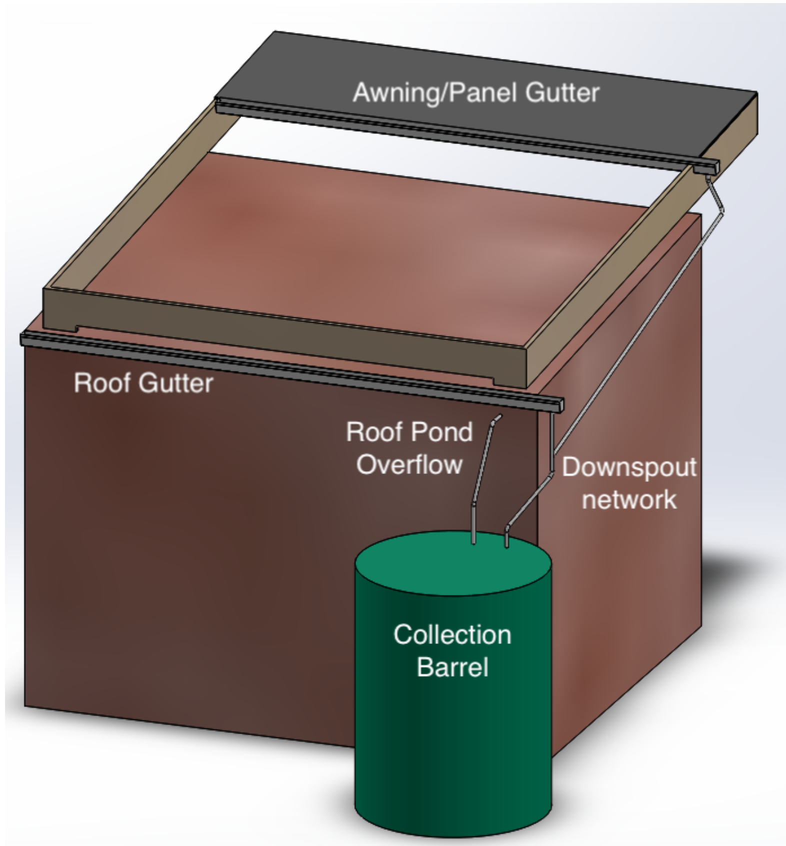


Figure 14. Demonstration of rainwater collection system on the tiny home

Using the geometry of the roof design, a gutter at the bottom of the slope collects water and stores it in a collection tank through a series of downspouts. This water can then be emptied, using a spout at the bottom of the tank, and used for most normal household uses.

5.2 Design Justification

To assure that the design was possible, analysis on the heat transfer into and out of the building was needed. The full-scale model was used for this analysis to additionally assure that the full-scale design was similarly possible. In a meeting with Dr. Peuker, who lectures at Cal Poly in DesignBuilder, an energy modeling program, it was suggested that the roof be avoided when modeling the home in DesignBuilder. This was because the insulation panels would be difficult to model as they move with human involvement which is not easily modeled. Therefore, to complete the analysis, the tiny home's structure was modeled in DesignBuilder with insulation to code except for the roof. The roof was modeled as a piece of plywood to allow the heat through that would occur without a roof pond. The rendered 150 square foot model in DesignBuilder is shown in Figure 15.

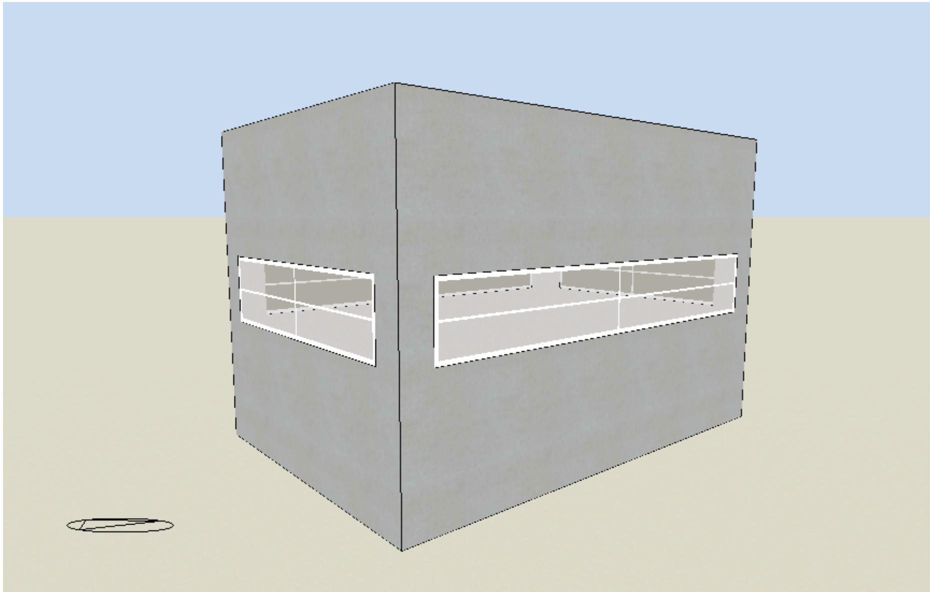


Figure 15. Rendered tiny home in DesignBuilder

DesignBuilder uses past weather data from San Luis Obispo along with the suns radiation and other parameters to find the inside temperatures that would result from the design. Running the programs simulation (Figure 16) resulted in a high temperature of 89°F and a low temperature of 52°F.

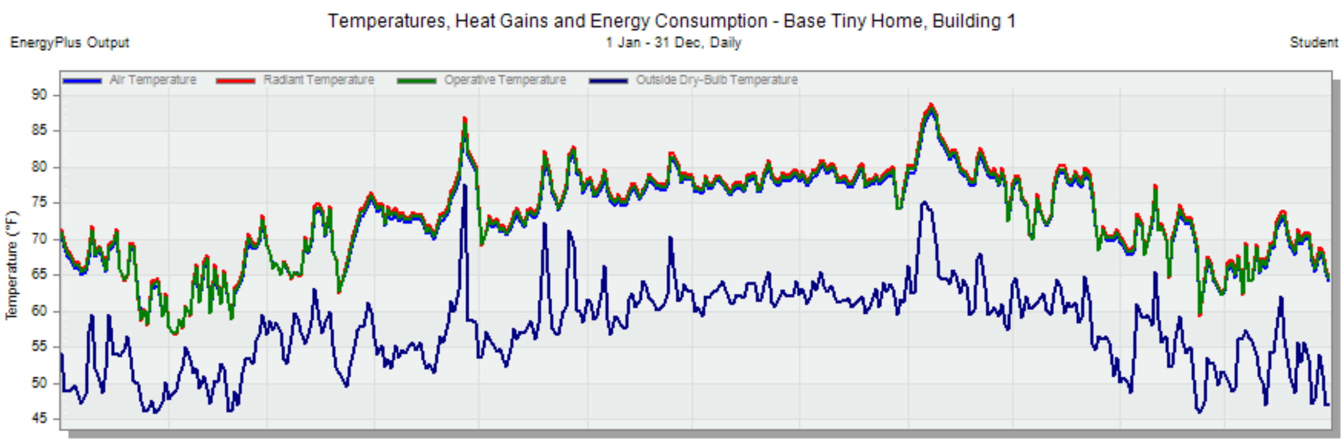


Figure 16. DesignBuilder data from year-round simulation of the tiny home in San Luis Obispo.

In the specifications detailed early in the project, it was decided the tiny home should stay within 68°F and 76°F. Using the equation

$$Q = mc\Delta T \ ,$$

The amount of energy required to heat or cool the home to the desired temperatures was found. Where m and c are properties of air. The energy, Q, was then used to find the temperature difference of the water when absorbing or radiating that amount of heat out of or into the tiny home. To heat the home from 52°F to 68°F, the water would experience a temperature drop of just

0.0941°F. Similarly, to cool the home from 89°F to 76°F, the water would experience a temperature rise of just 0.0737°F. This means that relatively small fluctuations in water temperature are enough to cause large heating or cooling effects inside the home. This certifies that the roof pond system for heating and cooling is very much possible, as long as the insulation panels are used correctly, and the home is consistently exposed to the sun's radiation. Hand calculations for this analysis can be seen in Appendix F.

This method was also verified on the model tiny home built for the verification prototype. It displayed a similar maximum water temperature difference of 0.0942°F.

5.3 Material Selection

The design of the mechanical systems for the tiny home are largely dependent on roof space, and our team placed a great emphasis on maximizing this resource. As a result, many of our design choices reflected this limiting factor. First, the area of the roof was expanded by including an awning. This supplied numerous benefits to multiple subsystems by providing a place to mount the solar panels without covering the roof pond, allowing for the insulation panels to be fully retracted rather than partially covering some of the roof pond, and increasing the total surface area for the rainwater collection system. Second, the design has numerous features that work to benefit multiple subsystems. And in the full-scale model, the square bars and z-mounts used for the solar panel assembly allow for enough vertical clearance for the insulation panels to be stored underneath the solar panels when they are fully retracted. The low slope of the roof pond prevents fallen debris such as branches and leaves from collecting heavily on the pond covers while also allowing a slope for water to be collected. The polycarbonate material selected for the roof cover works ensure the durability and longevity of the system as it is resistant to breaking down under UV-light, has high impact strength, and is rated for heavy weather conditions. Additionally, in the full-scale model, the square bars and z-mounts used for the solar panel assembly allow for enough vertical clearance for the insulation panels to be stored underneath the solar panels when they are fully retracted.

The roof pond spans the entire area of the structure's roof. This was done as it is perhaps the most innovative and creative aspect of the project and maximizing the area allows for the maximum effectiveness in its function, as conductive and convective heat transfer are surface area dependent. Additionally, aluminum sheet metal was selected for the roof deck material for its higher thermal conductivity compared to that of steel and for its cost effectiveness and availability to that of copper. The pond frame is made of standard fir two by four studs for their cost effectiveness and manufacturability. Although deflections are far less of a concern with a smaller design and less water pressure to account for, the switch to corrugated sheet metal fixed these issues. However, in the full-scale model, deflection analysis should be completed. Similarly, the weight of the roof pond system has become less of a concern with our scaled down model and actually helps to hold the roof pond structure in place.

The insulation panels are made of polystyrene insulation for their lightweight and cost-effective properties. Additionally, steel channels are used to provide the panels with added structure and rigidity, while the sheet metal protects the panels from exterior damage. The movement system is entirely powered through user input to maximize the energy efficiency of the tiny home. This allows for the movement system to be used in nearly any weather condition and in the absence of adequate solar power.

5.4 Safety, Maintenance, & Repair Considerations

Each subsystem was designed to present little to no risk to the user. The final design features substantial weight mounted about the user's head. Specific attention was placed on the structural integrity and stability of the system. Additionally, reliability was a key component of the design process, as per the user's demands. The movement systems are all designed with simple mechanics including gears, chains, and slides. These components, along with most of the framing elements, are made of durable materials and can be easily replaced using simple tools and at low cost. Additional safety and hazard prevention information can be found in Appendix E.

5.5 Cost Analysis Summary

One of most prominent concerns for this project has come from securing adequate funds. With the new design having a smaller scale, the project's budget has become more manageable. Additionally, many items were selected with cost effectiveness and availability in mind, as the majority of the structural components can be acquired at a local hardware store and be fabricated with relatively common tools. More specialty items such as the bearings and sprockets require being purchased from online vendors. It is also worth noting that various items can and have been sourced be repurposing old projects or abandoned materials.

The planned major subsystems can be broken down by cost as follows:

- Roof Pond Assembly - $266.64
- Insulation Panel Assembly and Movement- $286.62
- Building Structure - $398.65
- Rainwater Collection System - $139.03 (not built due to cost)
- Solar Panel Assembly - $100.87 (not built due to cost)
- Estimated Taxes and Shipping - $156.29
- **Estimated Total Cost - $1108.20**

The final cost for the solar panel assembly is with the purchased solar panel accounting for $86.87 and mounting hardware accounting for the remain $14. However, due to lack of time and funding at the end of building, the solar panel assembly was left out of the verification prototype. Our team decided that this system is already proven to work, and thus was not necessary to include in the verification prototype. The most expensive items in this subassembly are the large raw material items: the sheet metal, plywood, 2"x4" studs, and 4'x8' insulation panels. The insulation panel assembly has specialty items that require sourcing, such as the raw sheet metal to cover the panels or the bearings for the movement system. The rainwater collection system, also not added to the final verification prototype for similar reasons, featured items that could easily be found at local hardware stores at a relatively inexpensive cost, except for the collection tank being sourced online for $72.98. A full planned list of materials for the small-scale model purchases can be found in Appendix G. This list includes all systems (rainwater and solar).

5.6 Concerns with Final Design

As a result of losing our sponsor and architect, key factors such as build location and additional funding were no longer available to us. This project was created through the combined effort of our team and our sponsor and did our best to uphold the initial vision of the project through our final work. In addition, this change in group composition required the group to devise a method to mount the mechanical systems in a way that simulates the group's intended goals for the final design. Various ideas were brainstormed, such as using manufactured crates or shipping containers. A wood frame was pursued as it was the cheapest option and is the most similar to a typical tiny home. Additionally, the solar and rainwater assemblies were not built on the final verification prototype due to lack of need to test and budget.

6.0 Manufacturing Plan

To complete the final design, the materials needed to be resourced from outside venders. In the following section, we outline where we sourced our materials and how the final design was built. We also provide pictures of our verification prototype, and recommendations for the future. A summary of the manufacturing plan can be seen in Appendix H.

6.1 Procurement

We procured as many materials as possible from local home improvement retailers, such as Home Depot. This made the procurement process easier to replicate. Specialty parts such as bearings and gears were ordered through the internet. Raw metal materials were purchased from B&B Steel Supply in Santa Maria, which sells metal for cheaper than home improvement stores and stocks industrial-sized metal that cannot be found elsewhere. Lastly, one of our team members had a 3D printer, and we used that to print the connectors to attach the sprockets and hand-crank to the metal rod, and to print the spindles. A summary of our budget used to build the final prototype is shown in Table 5.

Table 5. Summary of Budget Allocations

Item Category	Cost ($)
Internal Pond Frame	47.99
Roof Deck	29.73
Pond Cover	188.92
Pond Insulation Panels	131.89
Insulation Panel Tracks	0*
Insulation Panel Movement System	154.73
Building Structure	398.65

*Materials were found or recycled from previous projects

The pond frame consists of wood, screws, staples, and pond liner which were all available at Home Depot. The roof deck is similar, and all materials were also purchased at Home Depot. For the pond cover, all materials were found at Home Depot except for the clear poly carbonate twin wall which was purchased from the student machine shops excess materials. The insulation panel assembly has a greater variety of places where materials were procured: Home Depot, B&B Steel

Supply, TAP Plastics, BearingsDirect, VEX Robotics, and Harbor Freight. To see the list of all materials and where they were purchased, see Appendix I for the indented Bill of Materials.

Our team submitted a proposal to the CPConnect grant, and we were lucky enough to receive $1108 for this project from the grant. As of now we have used all our funds allotted.

6.2 Manufacturing

A crucial part of our design is that no part is custom or requires specialized manufacturing. We were able to do all the manufacturing ourselves, ensuring the building process is repeatable, as per our sponsor's needs. The only manufacturing step close to a custom part is cutting raw materials to length. Other than using the waterjet to cut the sheet metal (cut plans can be found in Appendix J), we built the rest of the project in an area just outside of Bonderson or inside the Bonderson Machine Shop. We did not outsource any manufacturing, as there was nothing in the design that required it. In the following section, the manufacturing process that was followed during the building process is listed for each section of the final product.

Housing Frame

1. Cut standard 2x4 studs to appropriate lengths according to the cut sheet found in Appendix J.
2. Arrange cut 2x4's as shown in the assembly drawings found in Appendix J.
3. Once arranged properly, fasten the 2x4's together. First drill two equally spaced pilot holes at each joint and then use a countersink after to create conical hole. Drive a 3" wooden deck screw into the hole to join the pieces.
4. After creating the base frame and the appropriate side frames, repeat the steps provided in Step 3 to join these frame pieces together. First use a drill bit, followed by a counter sink, and finish with driving a screw to join the frame pieces together.
5. Once the frame has been assembled, cut plywood sheathing to size using a table saw. For sizing, it is advantageous to also measure the outer dimensions of the assembled frame for a cleaner and more true fit.
6. With the outer plywood sheathing cut to size, fasten the sheathing to the assembled housing frame by first drilling pilot holes with a drill bit then driving screws through the plywood and into the 2x4 studs. Space the screws approximately 18 inches apart on every stud.
7. Insulate every gap in the studs using 2" hard foam insulation. Measure each gap, then cut the insulation using a utility knife, and press insulation into place.
8. Attach casters to bottom of housing frame.
9. Cut hole in plywood on one wall for door. Attach door hinges and latch.

Roof Pond

1. Begin by preparing the inner roof pond frame. Similar to the construction process used to create the frame pieces for the housing frame, cut lengths of 2x4's to the appropriate size (which can be found on the cut sheet in Appendix J).

2. Assemble the cut lengths of 2x4 as shown in the assembly drawing found in Appendix J. Join the pieces together, first using a drill bit for pilot holes and then driving screws through the holes.
3. Establish a bottom face to the newly created frame. Cut the corrugated steel to match the size of the bottom face of the frame and secure it using metal-to-wood screws. If the screws are not self-tapping, use drill bits to create pilot holes before driving in the screws. Screws should be placed approximately 12 inches apart along each 2x4.
4. Place the assembled inner pond frame on top of the fully constructed housing frame with the piece of corrugated steel as the lowest part of the stack.
5. Measure and cut the ¾" Plywood panels that will encapsule the rood pond (the dimensions are shown attached in Appendix J). Use a table or circular saw for long straight cuts and a jig saw for more precise cuts and inside corners.
6. Assemble the cut pieces of ¾" plywood as shown on the assembly drawing in Appendix J. Begin fastening the plywood pieces to each other on top of the combined housing frame and around the internal pond frame by first drilling pilot holes then securing the pieces by driving screws. Fasteners should be spaced 3 inches apart as needed.
7. Install the pond liner by laying it flush on the inside of the internal pond frame constructed out of 2x4's. The liner should not be too tight as to prevent ripping and should conform to the general geometry of the pond frame. Ensure that the liner covers the top of the internal pond frame 2x4's before cutting away the excess liner. Secure the liner to the frame using a staple gun and outdoor use industrial staples. Space the staples every 3 to 4 inches.

Insulation Panels

1. Score polystyrene insulation board with utility knife, break on line
2. Create cut file on Illustrator. Send to waterjet technicians. Leave sheet metal next to waterjet and wait several days.
3. Bend sheet metal into 2" thick channels using sheet metal brake. Be careful to bend each angle to 90 degrees
4. Place caulk on top of steel channel and place sheet metal on top of panel
5. Use self-tapping sheet metal screws to secure sheet metal to steel channel, sealing the insulation panel from the elements
6. Pre-drill and countersink holes in UHMW plastic strips
7. Use self-tapping sheet metal screws to secure plastic strips to insulation panels
8. Use self-tapping sheet metal screws to secure grabber plates to insulation panels
9. Pre-drill holes to screw I-bolts into insulation panels. Screw in I-bolts.

Insulation Panel Retraction System

1. Cut 1" OD steel tubes to proper length using chop saw with metal blade
2. Drill 1.25" hole in side of plywood roof pond frame where 1" pipe is to go.
3. Drill holes in plywood structure to stick bolts through to secure bearings to structure
4. Secure bearings to structure
5. Using an angle grinder, grind down 1" tube slightly in order to fit inside 1" bore bearing hole

6. Attach 3D printed rope spindle and gears to steel rods, secure using 4mm hex head set screw
7. Use chain breaker to break chain to appropriate length.
8. Drill holes in A36 steel angle and countersink
9. Screw A36 steel angle into roof pond frame using 3/4” wood screws

Polycarbonate panels

1. Measure the dimensions of the roof pond frame. A frame needs to be constructed to support the polycarbonate panels; otherwise, the panels will sag in the middle an interfere with the insulation panel movement system.
2. Since each polycarbonate sheet is 2 feet high, a rectangular frame will be made from steel that is the width of the roof pond frame and the height of two 2-foot polycarbonate sheets. There will also be a bar that goes through the middle of the rectangle where the two polycarbonate panels join. Cut 1” OD steel tube to the lengths shown in Appendix J.
3. Weld together steel frame. Begin by tacking each joint with a small weld and then checking to make sure the rectangle is square. Then fully weld joints, welding all joints except for the top face where the polycarbonate will sit. This ensures that there will be no air gap between the panels and the steel frame due to the heigh of the weld.
4. Drill holes through the steel frame every 12 inches. The holes should be big enough to fit the threads of a wood screw, but not have the head go through.
5. Fasten the frame to the top of the roof pond plywood with wood screws.
6. Cut the polycarbonate panels to the width of the steel frame.
7. Pre-drill holes in the polycarbonate and steel frame, and then attach the polycarbonate using self-tapping metal screws.

6.3 Assembly

After the frame of the tiny home was completed, with the cut insulation board and plywood, the roof was assembled. The frame of the roof pond structure was added and screwed onto the tiny home frame first. The second step was adding the frame of the water pond, shown in Figure 17.

Figure 17. Black pond liner covering frame which is fitted inside the plywood

Once the frame was placed into the roof frame, we found that it did not need fastening as the clearance was so small that it would not move in any way. The pond liner was then placed on top of the roof frame and stapled above the water line using a staple gun (Figure 17).

Figure 18. Team member Cam wearing his PPE while operating the staple gun

Extra pond liner material was cut away with a razorblade to avoid friction with the sliding of the insulation panels. The insulation panels were the next step. The cut tracks were fastened to the sides of the roof frame as shown in Figure 19.

Figure 19. A36 Steel angle makes up the tracks for the insulation panels.

The insulation panels were assembled by screwing the cut and bent sheet metal around the cut insulation board. They were then lined with plastic strips to lower friction against the tracks. After, they were placed on top of the metal tracks, placing the bottom panel in first. While placing the polycarbonate panels on top of the tiny home frame, it was found that their deflection caused friction against the insulation panels while moving. As shown in Figure 20, a steel frame was built to fix this issue.

Figure 20. Steel frame for polycarbonate panels before panels are screwed down

After reassuring that the panels moved smoothly, the polycarbonate cover was screwed into place, and the assembly was complete. Figure 21 displays the final product before painting.

Figure 21. Completed scaled-down tiny home. Just needs paint!

In Figure 21, all parts of the roof pond system are displayed before the addition of the polycarbonate panels to show the complete system. The insulation panels, the tracks they slide on, and all gears are displayed.

6.4 Challenges and Recommendations

When we finished the tiny home frame with the plywood siding, we realized that the plywood would have to be lowered to place the roof frame on top. This required extra time and work to unscrew all plywood and reattach it 2 inches lower. We recommend that this be thought about and measured before adding the plywood panels to the siding of the tiny home frame. Another issue we came across in the building process was the fitting of the pond frame into the roof frame. Tolerances were too small to measure and consider when cutting the pond frame materials, leading it to be a tight fit inside the roof frame. To avoid this, we recommend placing the pond frame first, before attaching the roof frame. It is important, however, to remember that the pond frame must not be wider than the frame of the tiny home and that it must be large enough to have be stable on top of the tiny home frames open top. A third recommendation for the assembly would be dealing with the insulation panels. The tracks that attach to the sides of the roof frame must be assembled with the placement of the insulation panels. The bottom track and panel should be placed first, and then the top track and insulation panel. We first attached both tracks and found that we could not insert the bottom insulation panel when the top track was attached, so we had to take off one track to fix the issue. On a side note, tolerance is important when cutting the sheet metal and insulation board. Even though we would slightly change the way we assembled the tiny home if done again, all changes were reversible and did not impair or damage the design.

7.0 Design Verification

This section discusses the final design of the mechanical and structural systems for the tiny home. It also considers the safety, maintenance, repair considerations; discusses why specific parts and materials were chosen; and summarizes the cost analysis associated with the final design. It is important to note that substantial changes have been made regarding the scale and design feasibility of the final design.

7.1 Final Selected Design

Our final design focuses on showing the abilities of sustainability-driven design, featuring a roof-mounted pond system with actuating insulation panels for a blend of both active and passive heating and cooling, creating an adaptive climate control system for the home. The original intent of the home was to have mounted solar panels on the roof, thus allowing the home to be electrified for fully off-grid living. Additionally, a rainwater collection system using the geometry of the roof and a storage tank was strongly considered. Due to lack of funding and space to fulfill these ideas, the team chose to focus on ensuring the completion of the roof pond system. The user manual for this design is included in Appendix K.

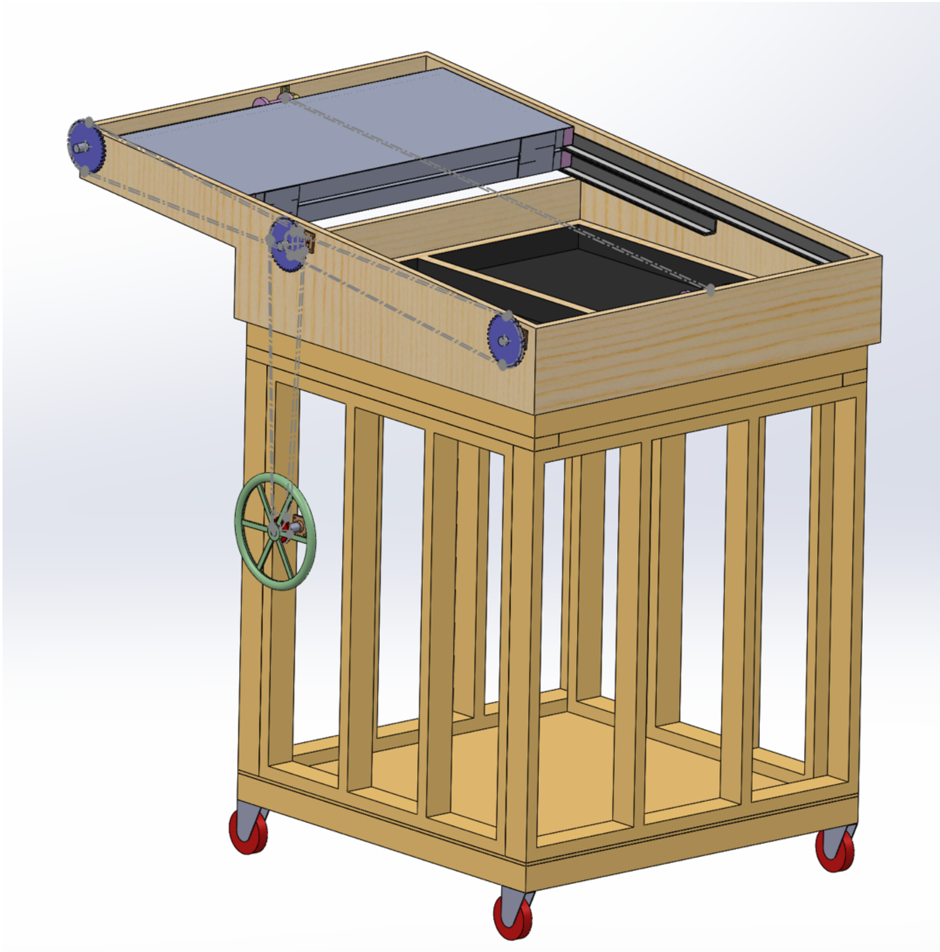


Figure 22. CAD Model of Tiny Home, shown without wall insulation and sheathing

Shown in Figure 22, the final design is a scaled down model of our previous design. Rather than design the mechanical systems for a 10’ by 12’ tiny home, our dimensions are now 4’ by 6’. The home itself is a 4’ by 4’ cube framed out of standard 2” x 4” framing studs while the awning overhangs the door to provide home with an additional 2’ in profile length.

7.2 Design Specification Verification

As mentioned previously, the final design is a scaled down model without rainwater or solar collection systems. Without the need for confirming these additional specifications, the final product must only satisfy the following: the Tiny Home Model must cost less than \$1100, be of proportional size, have an average temperature of 72 ± 5°F, and have comparable insulation values.

The final prototype was built using \$1054, differing from the original Intended Bill of Materials due to increased prices of wood – without the added prices of the rainwater system and the solar panel. The tiny home is also built to proportional size, with the water height around half the full-scale model. The model tiny home was around 7% of the full-scale cubic feet, however, due to the high heat capacity of water, the difference between the temperature rise of the water with the extra heat added from the hot air inside the full-scale model to that of the small model we built, was only 0.0942°F (Appendix F). In other words, our roof pond is almost perfectly scaled down from the full-scale design. The full-scale design was designed to have around R-21 to R-28 insulation. For the scaled down model, we decided R-13 would be sufficient for a much smaller space. Finally, our data revealed that the lowest and highest temperatures recorded in the model tiny home were around 58 and 73°F. The small-scale model was expected to hold temperatures from 65 to 75°F, however, it did not. The full-scale design should be able to achieve these temperatures with tighter insulation and better regulation of the insulation panels would result in a better temperature fluctuation. Additionally, the small-scale model lacks windows, which allow for manual temperature regulation, so all heating and cooling comes from the roof pond system.

The final product also satisfied the gear and weight bearing capabilities described in the Specifications section. The gear system is able to gently rise and lower the insulation panels smoothly with very little effort and was not tiring after 5 runs. The structure of the roof pond is able to hold over 200 lbs. of weight without deflecting.

7.3 Testing Description

To verify the tiny home model, four different testing procedures were created. The tests verified lower indoor temperatures during a hot day, compared indoor temperatures between a sunny versus cloudy day and building orientation, and certified that there are no leaks or issues with the rainwater collection system.

During the "Hot Day" test, the tiny home was placed outside in the sun with the insulation panels closed after being open the night before. Temperature readings were taken throughout the day and night and the highest indoor temperature was compared with the 70 ± 5°F indoor temperature specification (see Appendix L for the full testing procedure). During the testing duration, however, there were no days considered hot (above 85°F) and the test was therefore postponed.

The rainwater test was also postponed as the budget did not cover the rainwater system (see Appendix M for full procedure). Furthermore, there was no rain during the allotted testing period. This test, however, would be completed by placing the tiny home in an open area to collect as much rainwater as possible. The tiny home should collect the square footage multiplied by the rainfall. This number is compared to the actual volume of water in the collection tank.

The "Orientation Test" was a third test planned but unfortunately, time during the testing period was limited. This test, which can be seen in further detail in Appendix N, lasted four days with similar weather, the tiny home would be placed in the sun and rotated 90° every day. The high weather temperatures would be compared to the maximum indoor temperatures leading to a preferred orientation of the tiny home. Even though this test would have added verification to the design, for now, the tiny home was be placed facing north, to facilitate the most possible radiation exposure in the water. All tests and their corresponding testing dates can be seen in the Design Verification Plan and Report (DVPR) in Appendix P.

For the “Sunny versus Cloudy” test, the tiny home was placed outside in the sun for a total of 7 days. Indoor temperature readings were continuously recorded using a digital thermometer data logger. The data logger had two ports for two different temperature readings. As seen in Figure 23, the thermometers were placed in the roof pond’s water and inside the tiny home.

Figure 23. Thermometer locations for visual aid

The inside thermometer was placed on top of a sign, shown in Figure 24, so that the temperature recording was from the center of the tiny home and did not have additional error because of small proximity to the walls or water pond. The insulation panel pattern was switched from open during the night/closed during the day to open during the day/closed at night to see the effects of the insulation panels. During testing, weather data was recorded. The first three days were mostly cloudy, however, after the rest of the days were sunny, allowing for a comparison between the two. For this test procedure, see Appendix O.

Figure 24. Temperature probe (circled) hanging in middle of tiny home

In the future, better testing could result from a longer and more diverse weather period. For perfect testing conditions, the roof pond would be exposed to sun for the entire duration of the day and the scheduling of the insulation panels would be better regulated. With a more diverse weather period, the inside temperature could be examined from a very hot day and a very cold day, resulting in further, more extreme tests.

7.4 Test Results

To gather our test results, the thermometer logger was collected from the tiny home and the data loaded onto a computer in an Excel file. The results of this test, over a four-day period, starting on May 30thth at 12:00 AM and ending on June 2nd at 6:00 PM are shown in Figure 25. The local outside temperature is also shown for comparison.

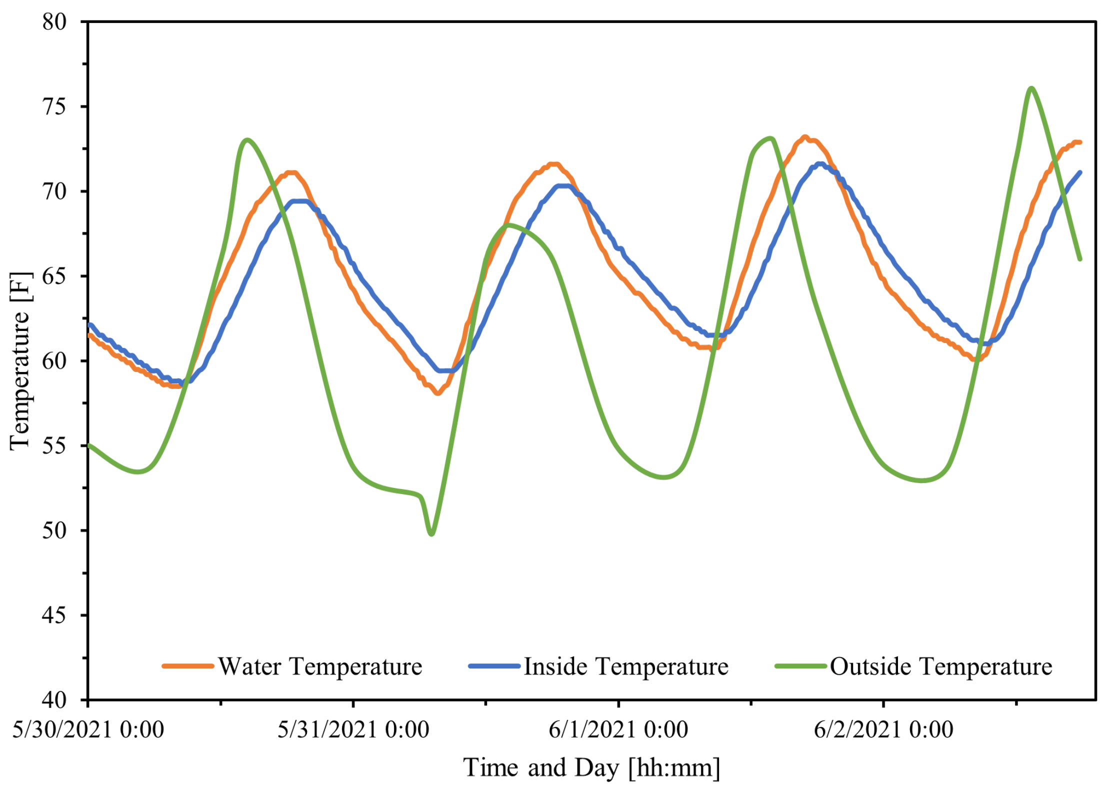


Figure 25. Graph of temperature over time

As shown in Figure 25, the interior temperature was kept in a very mild range inside the home. At the lowest, the temperature inside the home was 58 degrees, and at the highest, the temperature was 73 degrees. During this period, the insulation panels were placed on the home during the day of off at night. During this period, the outside temperature fluctuated from a low of 50 degrees to a high of 77 degrees. Our data shows that the roof pond system is capable of keeping the home within comfortable temperatures.

We also tested for a second range from May 19th at 12:00 AM to May 23rd at 12:00 PM which yielded similar results and can be seen in Figure 26. However, with this set of data the insulation panels were kept off the home during the day and placed on at night.

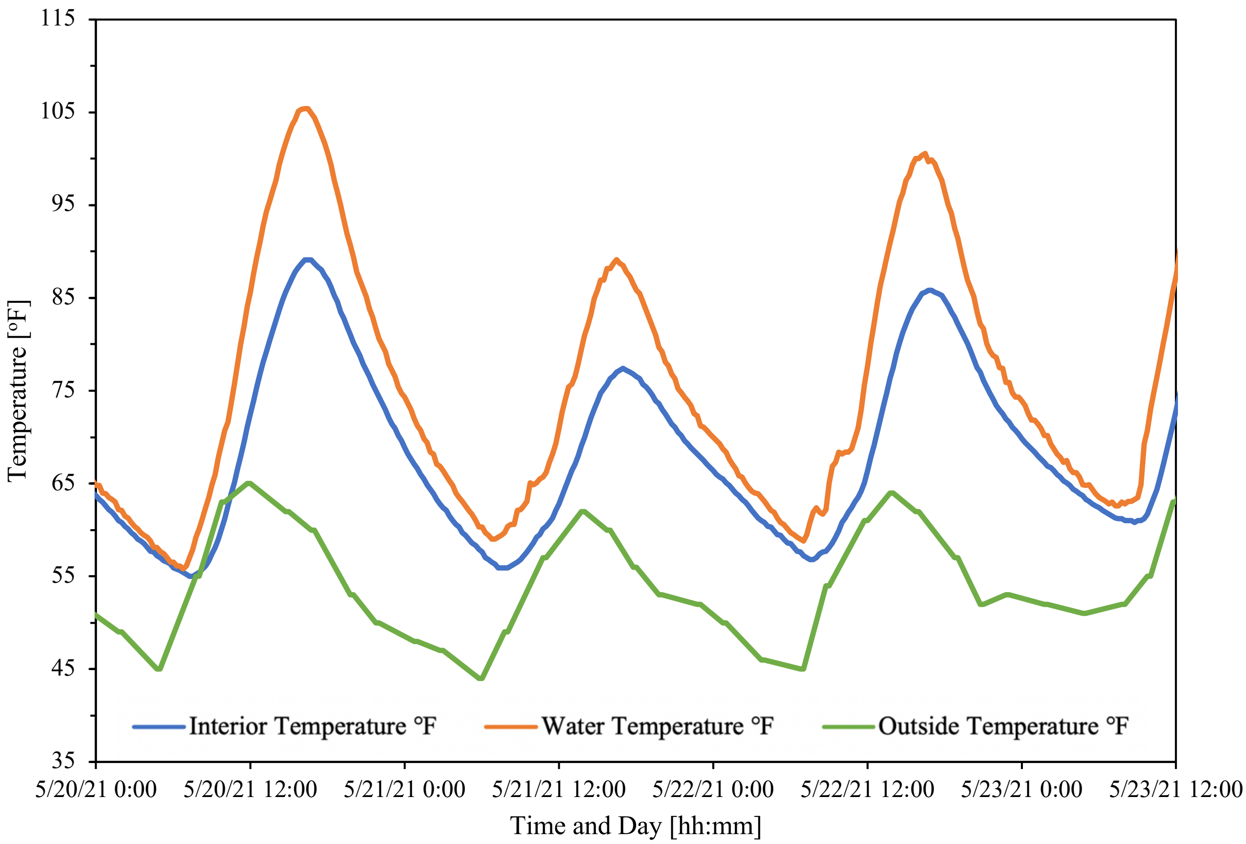


Figure 26. Graph of temperature over time for second data collection

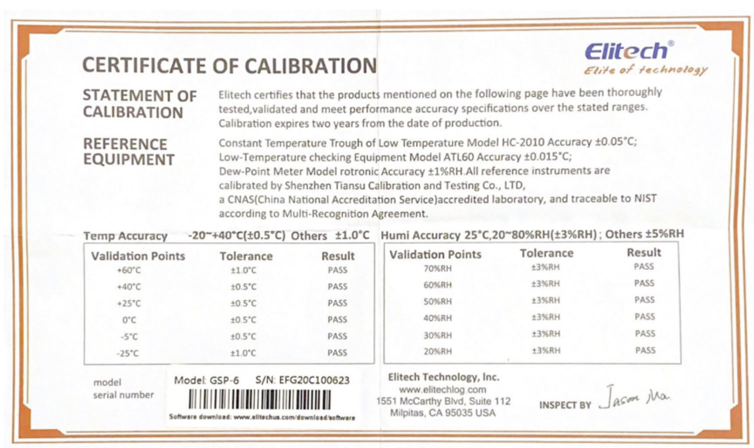
As seen in Figure 26, even during a 65°F day, the water reached temperatures above 105°F proving that when open to the sun, the inside temperature can still be kept a very warm 90°F. Therefore, the tiny home can heat the space very well.

When comparing Figure 25 and 26, with the insulation panels covered during the day there is much less of a peak to the high temperature of the day and the temperatures are much milder. In Figure 26, the peaks are much more evident and result in much higher temperatures.

To measure the uncertainty of our data, we performed a calibration test on our thermometer. In our initial testing procedure, we had planned to dip our thermometer in boiling water, because we knew that this temperature should be 212°F, and the difference between the thermometer reading and 212° F would be the bias uncertainty. However, we discovered our thermometer does not read above 180° F, so we had to find a new method. We found on the internet that the other leading method of finding thermometer accuracy, besides the boiling water test, was to create a small ice bath which will be at exactly 32° F. We created this by filling a cup to the top with ice, and then filling with water. We dipped the thermometer into the cup and swirled it around until the temperature reading was steady. As shown in Figure 27, our thermometer read exactly 32.0° F, leading us to believe that our thermometer has no bias uncertainty. However, to be more cautious in our total uncertainty calculations, we will be using the uncertainty provided by the manufacturer, as shown in Figure 28.

Figure 27. Measuring accuracy of thermometer in ice bath.

To find the precision uncertainty, we divided the resolution of or thermometer in half. The resolution of our thermometer is 0.1 degrees, so the precision uncertainty is 0.05 degrees. Included in the packaging with our thermometer we were given the following certificate of calibration (Figure 2), which states the error is ±0.5 degrees Celsius from –25 to +40° C.



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CERTIFICATE OF CALIBRATION

STATEMENT OF CALIBRATION: Elitech certifies that the products mentioned on the following page have been thoroughly tested,validated and meet performance accuracy specifications over the stated ranges. Calibration expires two years from the date of production.

REFERENCE EQUIPMENT: Constant Temperature Trough of Low Temperature Model HC-2010 Accuracy ±0.05°C; Low-Temperature checking Equipment Model ATL60 Accuracy ±0.015°C; Dew-Point Meter Model rotronic Accuracy ±1%RH.All reference instruments are calibrated by Shenzhen Tiansu Calibration and Testing Co., LTD, a CNAS(China National Accreditation Service)accredited laboratory, and traceable to NIST according to Multi-Recognition Agreement.

Temp Accuracy -20~+40°C(±0.5°C) Others ±1.0°C

Validation Points	Tolerance	Result
+60°C	±1.0°C	PASS
+40°C	±0.5°C	PASS
+25°C	±0.5°C	PASS
0°C	±0.5°C	PASS
-5°C	±0.5°C	PASS
-25°C	±1.0°C	PASS

Humi Accuracy 25°C,20~80%RH(±3%RH); Others ±5%RH

Validation Points	Tolerance	Result
70%RH	±3%RH	PASS
60%RH	±3%RH	PASS
50%RH	±3%RH	PASS
40%RH	±3%RH	PASS
30%RH	±3%RH	PASS
20%RH	±3%RH	PASS

model
serial number
Model: GSP-6 S/N: EFG20C100623
Software download: www.elitechus.com/download/software

Elitech Technology, Inc.
www.elitechlog.com
1551 McCarthy Blvd, Suite 112
Milpitas, CA 95035 USA

INSPECT BY Jason Ma

Figure 28. Certificate of Calibration for our thermometer device

We will take the values given as our bias uncertainty and perform error propagation by adding the squares of the two uncertainties and then taking the square root of the sum.

$$Error = \sqrt{(B_2 + \mathrm{P2})} = \sqrt{(0.05^2 + 0.52)} = \pm 0.502°\mathrm{C} = \pm 0.9°\mathrm{F}$$

Thus, our total uncertainty in our measurements is ±0.9°F. Humans are not very sensitive to temperature changes of less than 2°F. Our system is tested to ensure comfort for occupants, so an uncertainty of ±0.9°F will not change the validity of our results.

7.5 Assessment of Performance

The results of our data were very close to the desired results. We wanted the temperature inside the home to stay ±5 degrees from 70 degrees Fahrenheit. Our testing showed a temperature variation from 58 degrees to 65 degrees. On the two days we tested, the weather had a low of 51 degrees and a high of 65. We are still waiting on a period of warm weather to test out the proficiency of this design when the temperatures are more extreme. With the weather we were afforded, we feel that the roof pond did a great job of regulating the temperature inside the home.

7.6 Challenges and Lessons Learned

We experienced a couple of difficulties throughout the testing and analysis portion of the tiny home project. We would have preferred to start testing earlier to record more data and complete the Orientation and Hot Day tests. Without these tests, it was difficult to verify that our design works well when compared against some of our planned criteria. We have learned the importance of planning ahead and accounting for extended testing time.

Another issue we faced was the weather. During the beginning of our testing period, the weather was very cold and cloudy. This posed an issue to the quality of our results as the water was never able to heat up to keep the tiny home warm as it would in a real scenario. The lower temperature readings effected the comparison between the cloudy and sunny day temperatures, resulting in a larger difference than expected. In the future, with more testing time, we hope we can find days of weather that will work for our testing procedures.

8.0 Project Management

The tiny home project started off strong with great ideation sessions and hard researching. During the end of fall quarter, it started to seem evident that a full-scale tiny home would not be completed. To have continued with the full-scale model, the architectural drawings would have needed to have been completed during the middle or beginning of fall quarter. This is due to the process of permitting the building and the site and to give more time for building the final product. However, even through a couple of months of uncertainty, the tiny home team stayed positive and when time was running out, found a solution to still design and build a tiny home, just of smaller size. Then in middle-to-late winter quarter we developed our final design. To see the yearlong project management, see in Appendix Q.

If completed again, we would consider the longer testing time for this project and have started building earlier. The actual building phase of the project went according to plan and only took about two and a half weeks. However, our testing was dependent on weather. It would have been helpful to complete the build phase earlier, which would have allotted us more time to test; potentially giving us a wider range of weather conditions to analyze the home's performance in.

9.0 Conclusion and Recommendations

The Tiny House team created a solution where the tiny home was as sustainable as fiscally possible. There are many different aspects and mechanical systems within the overall full-scale tiny home system that were designed for the largest energy savings possible. For each prototype, the team tested and verified that the chosen system was the best choice based on price, durability, function, creativity, and innovation. We hope to one day witness the full-scale tiny home design.

9.1 Conclusions

We believe that our project, overall, was a success by two measures: First, it was an informative experience for our team, and second, the design worked as intended. Our team worked together for a full school year to complete this project, and we learned a lot along the way. By completing this project, each of our team members has significantly more project experience than before. We now have a hands-on project under our belt that will help us be prepared and confident when tackling industry projects. In particular, documenting our process, justifying design decisions, and procuring parts are very common tasks that a mechanical engineer must complete. Our exposure to these during the scope of this project means we are more likely to successfully handle them in the future. Additionally, most engineers in the field work in teams for long periods of time. This project constituted a significant amount of teamwork experience, a must-have for most potential employers. It must be said that our team had an easy time getting along, which is not always the case in the real world, so we did not have to learn how to reconcile with each other to continue the project. However, being able to successfully "click" with teammates and work efficiently in tandem is still a valuable skill that all of us gained.

Our second success comes from the result of the project itself, namely, that it worked. Our whole team was very excited about the roof pond concept, and we really wanted to see it perform well. We were especially enthusiastic about proving that the roof pond is a great way to heat and cool off-grid or low-budget homes and can be simple enough to implement anywhere. Our data shows that the concept does indeed function as intended and completing it on a small budget shows its versatility. Additionally, we were able to use mostly off the shelf parts which are familiar to contractors, so it would not be out of the question to implement our design in a livable home. For this reason, we consider the outcome of the project a success.

Despite our successes, we have had some less savory outcomes. The most glaring is the number of pivots we have had to make over the course of the year. When our initial project plans fell through, it was difficult for our team to pick up the pieces and find a new direction while staying true to the original ethos of the project. In hindsight, it would have been advantageous for us to have backup plans in place ahead of time, so that we could change direction quickly, without retracing our steps. Without contingency plans, we had multiple periods of time where the project was effectively stalled while we redefined our goals. We think the project went well. All things considered, the project in its current form accomplishes our goals. However, the project could have run smoother if we had made backup plans earlier on.

9.2 Future Recommendations

Our team ran into a few notable obstacles throughout the duration of this project. Due to limiting funding, resources, and available space, we had to adjust certain aspects of our project such as the size and scale of our build to match our budget and overall circumstance. Although we are confident that the scaled down nature of our build is representative a larger tiny home, we would recommend future teams to consider tests and plans for larger structures in combinations with results of our project. We decided to not incorporate both a water and solar collection system into our final verification prototype. Due to our limited budget, we felt that the plug-and-play nature of modern solar panels was a less economical use of the team's time and resources and thus decided to ensure that the roof pond system was built to our desired standards. Similarly, the rainwater collection system was not incorporated into our final design. Our team strongly recommends incorporating these concepts (or something similar) in future efforts to create a fully livable, off-grid tiny home.

The packaging of the roof pond assembly could be changed in the future to achieve better performance. In our verification prototype, the roof pond is open to the air. The polycarbonate sheet, which forms the low-slope roof shape, is situated above the insulation panels, as seen in Figure 29. There is an air gap at one end of the structure to allow the panels to slide through. This design created a number of problems that are not ideal for implementation on a real home. First, the polycarbonate created an area of increased temperatures and humidity underneath the sheet. This led to mold developing on the unpainted wood siding and corrosion on metal framing pieces. This also caused the sheet metal sheathing on the insulation panels to warp, which wreaked havoc on the tight tolerances needed for the panels to slide smoothly and catch each other reliably. Lastly, the high temperatures meant that the water in the pond would heat up more than necessary for the space's heating needs. This led to extremely high interior temperatures if the panels were left open during the hottest part of the day.

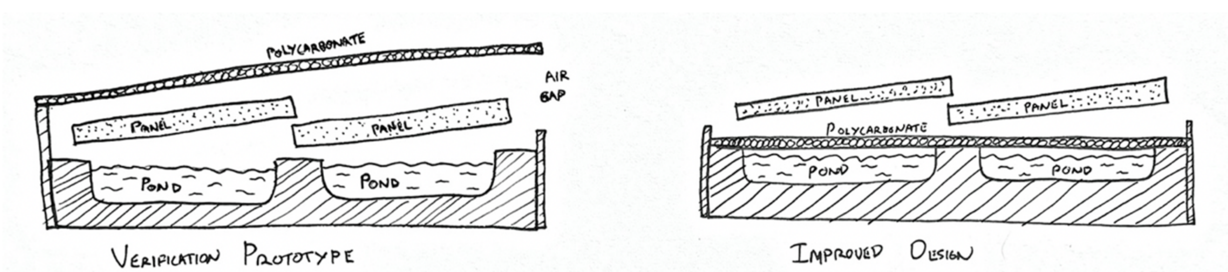


Figure 29. Pond Assembly Cross Section. Note that the structural pieces holding the pond, panels, and polycarbonate is not shown to improve clarity.

An improved design, as seen in Figure 29, could solve these problems. By placing the polycarbonate sheet below the insulation panels, the heat and corrosive effects would no longer affect the panels and their movement. This would create a more reliable movement system, which is important because the panel movement system must work for years on a lived-in tiny home. The lower polycarbonate sheet would also seal the ponds, removing the evaporation that the verification prototype experiences due to the air gap. A better sealed mass of water may also undergo smaller temperature swings, which would help the system perform in moderate climates.

Some componentry could also be improved. The verification prototype used 3d printed plastic hubs and spools with a single set screw fixing them to the rotating shafts. We printed these parts at a low infill, so they were not as strong as they could be. The single set screw design was susceptible to slipping on the shafts, because the shafts were slightly oval in cross-section. To accommodate, we tightened the set screws to a very high tension, which caused some parts to crack. In the future, we would recommend using a higher infill density for 3d printed parts, or forgoing plastic altogether in favor of metal componentry. These parts should also have two set screws to ensure good shaft contact, regardless of the shaft's cross section.

The chain system on the panel movement system would benefit from the addition of sprung chain tensioners. The chain connecting the driving crank to the panel movement shafts was prone to slippage, even at the shortest link length possible. Chain tensioners would allow the chain to be longer and thus easier to install, while also making the chain contact more consistent. This would be especially useful when considering serviceability because chains can wear out, stretch, or snap over time. The addition of tensioners would allow the system to accommodate for chain stretch and allow the user to replace the chain easily if it snaps.

In order to assist the user, a tiny home with a roof pond system could have a number of different aids. The most basic system would be a "thermostat" mounted in the home that shows outside, water, and inside temperatures. The user could then use this temperature data to decide when and how to move the roof insulation panels. A more advanced system could be programmed to notify the user when to move the panels through an auditory notification or a phone alert. This system could be adjusted to recommend movement based around the user's preferred indoor temperatures. Lastly, the most advanced system could remove the user entirely by automating the movement of the panels. In this scenario, the user would set a target range of temperatures and the control system would move the panels accordingly. However, a major drawback is that the control system would require energy to move the panels. This means the system would no longer be truly operable with no energy. For this reason, we recommend that the roof pond system always be implemented using human power to move the panels for tiny home applications.

9.3 Next Steps

We would love to offer guidance to potential future users of the roof pond system. To that end, anyone interested in building a home using this design should contact the team for consultation. We would be able to consult the user and ensure their home has the right pond, panel, and structure for their home design. Additionally, we could help the builder procure parts and manage the assembly, although they could use our report and user manual for this. Lastly, we would be able to instruct the user on how to get the best performance out of the system once they move in to the home.

References

[1] Majsztrik, John, et al. "SpringerLink." *Water Use and Treatment in Container-Grown Specialty Crop Production: A Review*, 21 Mar. 2017.

[2] "Tiny House Statistics [2020]: Market Size & Industry Growth." IPropertyManagement.com, /14 Aug. 2020, ipropertymanagement.com/research/tiny-home-statistics.

[3] "How Many Solar Panels Does It Take To Power a Tiny Home?" All About Tiny Houses, 11 Sept. 2020, allabouttinyhouses.com/378/solar-panels-tiny-house/.

[4] "About Greywater Reuse." Greywateraction.Org, greywateraction.org/greywater-reuse/

[5] "Greywater Systems." Graywater Systems | City of San Luis Obispo, CA, 2019, www.slocity.org/government/department-directory/utilities department/conservation/graywater-systems.

[6], Luke I. "Tiny House Permitting in San Luis Obispo." Cal Poly Digital Commons, 2018, digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1189&context=cmsp.

[7] International Living Future Institute. "Living Building Challenge 4.0." *living-future.org/lbc,* June 2019.

[8] Langston, Bryce. "Off-The-Grid Desert Living in a Tiny Earthen Home & Permaculture Community." *YouTube*, Living Big in a Tiny House, 15 Nov. 2019, www.youtube.com/watch?v=QDXPIM5dxLw.

[9] Pogue, Andrew. "This Solar-Powered Prefab in Seattle Raises the Bar for Sustainability." *Dwell*, Lucy Wang, 6 Mar. 2019, www.dwell.com/article/solar-studio-wittman-estes-9b3cf13b-d204a241.

[10] Tiny Home Tours. "The Ultimate Off The Grid Tiny House Homestead ~ Thriving In The Arizona Desert!" *YouTube*, 3 June 2018, www.youtube.com/watch?v=y-9pxpulqWc.

[11] Hayward, Mac. "A Writer's Prefab Retreat Sits Lightly Upon the Land in Joshua Tree." *Dwell*, Lucy Wang, 27 Nov. 2019, www.dwell.com/article/a-writers-prefab-retreat-sits-lightly-upon-the-land-in-joshua-tree-aeb86a7d.

[12] "7 Best Home Wind Turbines." *Tiny House Huge Ideas*, tinyhousehugeideas.com/best-wind-turbine-reviews/.

[13] Griswold, Kent. "Alternative and Renewable Energy Resources for Tiny Houses." *Tiny House Blog*, 29 Jan. 2016, tinyhouseblog.com/tiny-house/alternative-and-renewable-energy-resources-for-tiny-houses/.

[14] 康树人 , et al. *Solar House*. 26 Mar. 2014.

[15] 程波 . *A Solar Electricity-Generation, Energy-Accumulation Water-Heating Device*. 9 July 2009.

[16] 李万红 , and 李正 . *Solar Energy Household System*. 4 Sept. 2013.

[17] Bailey, Michael John. *Glass House Having a Rain Water Collection and Irrigation System*. 7 June 2009.

[18] Annavajjhala, Ravi, and Srinivasan Sivaram. *Intelligent and Efficient off-Grid Solar Home Energy System and Method Thereof*. 14 Nov. 2017.

[19] Vcelak, J, and E Novak. "IOP Conference Series: Earth and Environmental Science." *Energy Sustainable Living – Deep Renovation of Residential Building – PAVE*, 2019.

[20] S Energy News Weekly. "Gale Academic Onefile." *JinkoSolar Modules to Power Arc House at Solar Power International*, 23 Sept. 2016.

[21] Specht, Kathrin, et al. "ProQuest." *Urban Agriculture of the Future: an Overview of Sustainability Aspects of Food Production in and on Buildings*, Mar. 2014.

[22] Smith, E, and K Bani-Melhem. "ProQuest." *Grey Water Characterization and Treatment for Reuse in an Arid Environment*, June 2012.

[23] Purwasasmita, B S. "IOP Conference Series: Earth and Environmental Science." *Green Materials for Sustainable Development*, 2017.

[24] California Energy Commission. "*2019 Building Energy Efficiency Standards for Residential and Nonresidential Buildings*" December 2019. https://ww2.energy.ca.gov/2018publications/CEC-400-2018-020/CEC-400-2018-020-CMF.pdf

[25] Data.org. (n.d.). Retrieved October 12, 2020, from https://en.climate-data.org/north-america/united-states-of-america/california/san-luis-obispo-1445/

[26] Use of energy in homes - U.S. Energy Information Administration (EIA). (2021). Retrieved 1 June 2021, from https://www.eia.gov/energyexplained/use-of-energy/homes.php

Appendices

A. Quality Function Deployment
B. Pugh Matrices
C. Weighted Decision Matrix
D. Preliminary Analysis
E. Design Hazard Checklist
F. Design Verification Hand Calculations
G. Initial Intended Bill of Materials (Full systems)
H. Manufacturing Plan Summary Table
I. Final Project Budget Allocation Spreadsheet
J. Drawing Package – Cut plans for wood studs and other
K. User Manual
L. Testing Procedure – Hot Day
M. Testing Procedure – Rainwater Collection
N. Testing Procedure – Building Orientation
O. Design Verification Plan & Report (DVPR)
P. Testing Procedure – Sunny versus Cloudy
Q. Gantt Chart
R. Risk Assessment
S. Design FMEA

A. Quality Function Deployment

Correlations	
Positive	+
Negative	–
No Correlation	

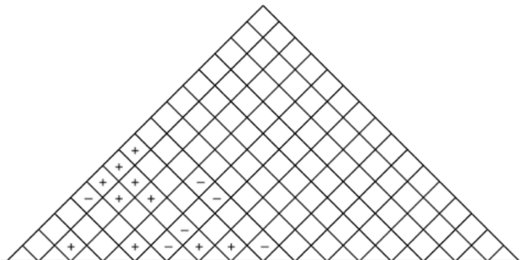
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: ______F82 Sustainable Tiny Home________

Revision Date: ______10/05/2020_____



Row #	Weight Chart	Relative Weight	WHO: Customers: Tiny Home Buyer	Low-income/Low cost Home Buyer	Traveler with needs of a "Home Base"	Manufacturer/Assembly Person	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants)
1		9%	10	10	9	2	9	Provides enough energy
2		10%	10	10	9	5	9	Water system
3		10%	8	10	9	7	9	Low cost
4		8%	6	7	5	8	9	Windows energy friendly
5		10%	10	10	9	6	9	Energy storage
6		9%	8	8	10	4	3	Low maintenance
7		9%	10	10	10	2	9	User friendly (energy systems)
8		7%	7	7	10	2	1	"Vacation home", can be left alone
9		10%	10	10	10	5	3	Water heater
10		9%	5	5	6	10	9	Mech. subsystems are transportable
11		9%	9	9	7	5	9	Aesthetic systems
12		0%						
13		0%						
14		0%						
15		0%						
16		0%						

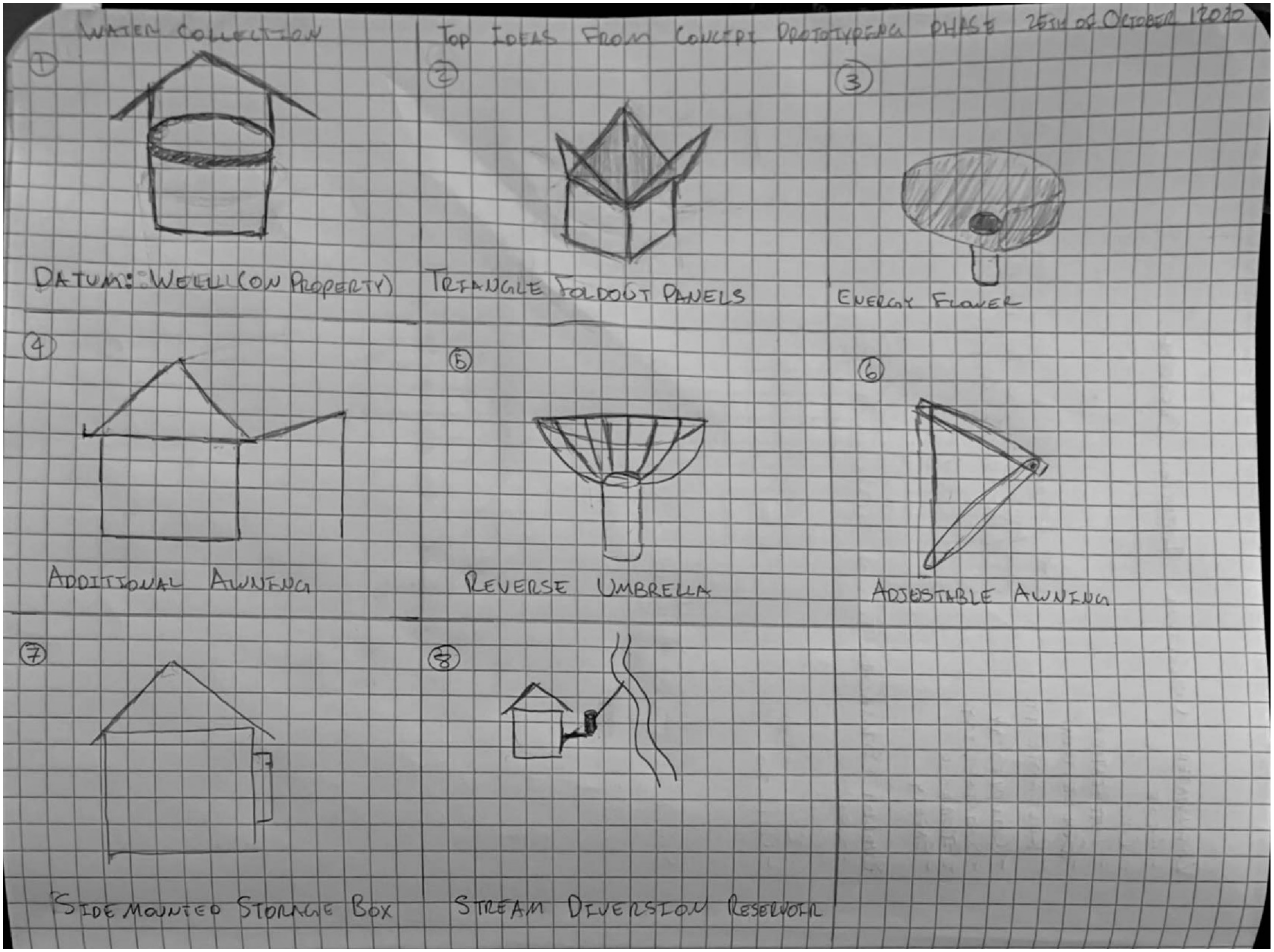
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Direction of Improvement	▲	▼	◇	◇	▼	▼	▼	▲	◇							
HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	Energy storage max/min	Water pressure	Total water flow rate	Window U-factor and SHGC	Cost of Materials	Weight of mech. Subsystem	Size of subsystem	Energy output min/max	Average temperature inside home							
Provides enough energy	●			▽	○		○	●	▽							
Water system		●	●		▽											
Low cost	○	▽	▽	▽	●		○	○	○							
Windows energy friendly				●	▽			▽	○							
Energy storage	●			▽	○	○	○	●	○							
Low maintenance	▽						▽	▽	○							
User friendly (energy systems)	○	▽	▽						●							
"Vacation home", can be left alone									▽							
Water heater		○	○		○	○	▽		▽							
Mech. subsystems are transportable	○				▽	●	●									
Aesthetic systems	○			▽	▽		●	○								

NOW: Curr. Products: Our Current Product	Regular House	Converted Van	Rest Stop	Apartment	Row #
3	5	2	1	5	1
5	5	2	2	5	2
1	1	4	5	3	3
3	3	2	1	2	4
4	2	5	1	2	5
4	3	4	5	4	6
3	4	3	5	5	7
5	3	1	5	4	8
2	5	2	2	5	9
3	1	5	1	1	10
5	4	4	2	3	11
					12
					13
					14
					15
					16

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	5000 kwH max capacity	40 psi	6 gpm	0.3	10,000	100 lbs	10 cubic feet	10kWH	70F							
	Max Relationship	9	9	9	9	9	9	9	9	9							
	Technical Importance Rating	289.2	138.9	138.9	113.1	215.7	140	264.6	244.9	218.6	0	0	0	0	0	0	0
	Relative Weight	16%	8%	8%	6%	12%	8%	15%	14%	12%	0%	0%	0%	0%	0%	0%	0%
Curr. Products	Our Current Product	1	1	1	1	1	1	1	1	1							
	Regular House	9	9	9	9	2	3	2	9	9							
	Converted Van	2	2	1	6	9	7	9	2	4							
	Rest Stop	2	5	5	4	9	1	2	9	3							
	Apartment	8	7	7	8	9	3	7	9	7							
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

B. Pugh Matrices

Water Collection

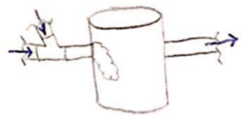


CRITERIA	①	②	③	④	⑤	⑥	⑦	⑧
USE OF SPACE	D	+	∅	+	∅	+	+	−
COST TO UTILIZE	A	−	∅	+	−	+	∅	−
INTEGRATION	T	+	+	+	+	+	∅	+
DESIGN COMPLEXITY	U	−	+	+	−	−	+	−
PASSIVE COLLECTION	M	+	+	+	+	+	∅	+
USER EFFORT	X	+	+	+	∅	∅	+	+
SUSTAINABILITY	D	∅	∅	∅	∅	∅	∅	−
STORAGE CAPACITY	A	∅	∅	∅	∅	∅	+	+
USER SAFETY	T	∅	∅	∅	∅	∅	∅	∅
CONSISTENCY	U	−	−	−	−	−	∅	−
CLEANING/SERVICE	M	−	+	−	+	∅	−	−
	X							
	D							
	A							
Σ+	T	4	5	6	3	4	4	4
Σ−	U	4	1	2	3	2	1	6
Σ+/−	M	∅	4	4	∅	2	3	-2

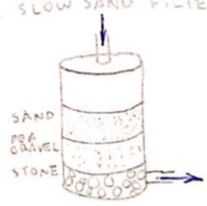
Water Filtration Systems

WAYS TO TREAT RAINWATER/GRAYWATER

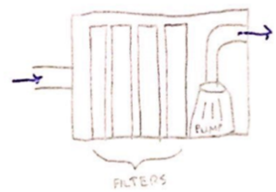
1. SETTLING TANK



2. SLOW SAND FILTER

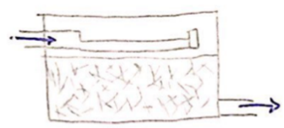


3. MANUFACTURED FILTER

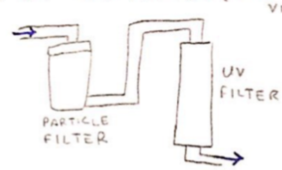


4. WETLAND FILTER

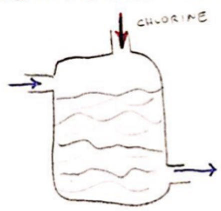
5. WOODCHIP FILTER



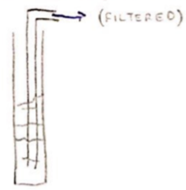
6. UV STERILIZER (ULTRA-VIOLET)



7. CHEMICAL DISINFECTION



8. DATUM: WELL WATER



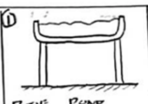
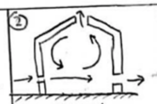
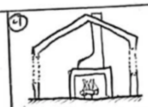
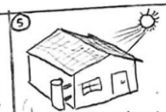
CRITERIA	(8) DATUM	1	2	3	4	5	6	7
LOW MAINTENANCE		S	+	−	−	−	+	−
ENERGY EFFICIENT		+	+	−	+	+	S	+
USER FRIENDLY		−	−	+	−	−	S	S
COST		+	+	−	+	+	−	+
SIZE OF SYSTEM		−	−	−	−	−	−	−
SPEED OF FILTRATION		S	−	S	−	−	+	+
ENVIRONMENTALLY FRIENDLY		+	+	+	+	+	+	−
AESTETICS		S	−	−	+	−	S	S
SUM (+)		3	4	2	4	3	3	3
SUM (−)		2	4	5	4	5	1	3
DIFFERENCE		1	∅	-3	∅	-2	2	∅

Energy Generation

CONCEPT / CRITERIA	CONNECTED TO GRID	ROOF SOLAR PANELS	HILLSIDE SOLAR PANELS	PUMP/TURBINE	RAINWATER TURBINES	HUMAN POWER	CREEK DRIVEN TURBINE	SOLAR FLOWER
ASTHETIC	DATUM	S	−	−	S	−	S	S
SMALL SIZE		+	−	−	+	+	+	−
ENERGY CREATING SIZE		−	S	−	−	−	−	−
TRANSPORTABLE		+	−	−	+	+	−	−
COST		+	−	−	S	−	−	−
FOOTPRINT		+	+	+	+	+	+	+
MAINTENENCE		−	−	−	S	+	−	−
RELIABILITY		−	−	−	−	−	−	−
WORKS SMALL SCALE		+	−	S	+	+	+	+
USER FRIENDLY		+	S	−	S	−	−	+
TOTAL	Ø	+3	−6	−7	+2	Ø	−3	−3

Pugh Matrix

Heating / Cooling

Concept / Criteria	①  Roof Pond	②  Passive Cooling	③  Creek-fed Swamp Cooler	④  Sealed / Fully Insulated	⑤  Solar-Powered Conventional	Ⓓ  Conventional Home
Aesthetic Appeal	+	S	−	S	S	DATUM
System Integration Potential	+	S	−	S	+	
Reliability	S	+	+	+	S	
Cost	−	+	+	+	−	
Sustainability	+	+	+	+	+	
Innovative	+	S	−	−	S	
Works for Setting	+	+	S	S	S	
Transportable	−	+	+	+	−	
Ease of Use	+	+	S	+	S	
Total	+4 ☆	+6 ☆	+1	+4	0	D (0)

C. Weighted Design Matrix

		Options													
		Concept 1		Concept 2		Concept 3		Concept 4		Concept 5		Concept 6	
		Roof panels, awning, roof pond, UV/sand		Roof panels, solar flower, passive cooling, UV/slow sand		Wind, storage box, sealed home, wetland filter		solar flower, reverse umbrella, passive cooling, manufactured		Roof Panels, Awning, Passive Cooling, Manufactured Filter		Hillside, Awning, Pond, UV/Sand Filter	
Criteria	**Weighting**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**
Cost	9	6	54	4	36	3	27	5	45	7	63	6	54
Use of Space/Size	4	8	32	7	28	6	24	6	24	9	36	7	28
Durability	7	7	49	6	42	6	42	5	35	9	63	7	49
Energy Output	6	8	48	7	42	2	12	4	24	8	48	6	36
Water Output	6	7	42	5	30	5	30	5	30	7	42	7	42
User Interface	2	6	12	7	14	5	10	7	14	8	16	6	12
Water Heating	6	8	48	4	24	4	24	4	24	4	24	8	48
Transportable	1	4	4	3	3	1	1	5	5	6	6	2	2
Aesthetic	4	4	16	7	28	6	24	7	28	9	36	4	16
Design Complexity	7	5	35	6	42	5	35	5	35	8	56	5	35
Sustainability	8	7	56	7	56	7	56	6	48	7	56	5	40
User Safety	10	6	60	8	80	8	80	8	80	7	70	5	50
Permitability	10	7	70	10	100	6	60	10	100	9	90	5	50
Maintenence	7	7	49	9	63	7	49	8	56	6	42	4	28
Innovation	10	9	90	2	20	3	30	3	30	2	20	6	60
Creativity	9	8	72	1	9	3	27	4	36	1	9	7	63
SUM			**737**		**617**		**531**		**614**		**677**		**613**

D. Preliminary Analysis

TWO PEOPLE → 5 kWh NEEDED PER DAY

STANDARD PANEL → 300 W RATING

DAILY GENERATION, FOR 5H. OF DAILY SUNLIGHT → 300W · 5H = 1500WH

PANELS NEEDED → $\frac{5\,kWh}{1500\,Wh}$ = 3.33 ≈ 4 PANELS

AVERAGE 300W PANEL SIZE → 5' x 3.5' = 17.5 FT²

TOTAL ARRAY → 4 PANELS $\left(\frac{17.5\ FT^2}{PANEL}\right) = \boxed{70\ FT^2}$

THIS SIZE IS SMALLER THAN THE MINIMUM ALLOWED SIZE OF 110 FT², APPROXIMATELY HALF THE SIZE OF THE HOME'S FOOTPRINT. THUS, THE ARRAY WILL BE ABLE TO PROVIDE ENOUGH POWER UNDER OUR SIZE CONSTRAINT.

WATER DEPTH, FROM PREVIOUS ROOF POND DATA — 6 - 8" ASSUME 8" FOR LARGER FACTOR OF SAFETY

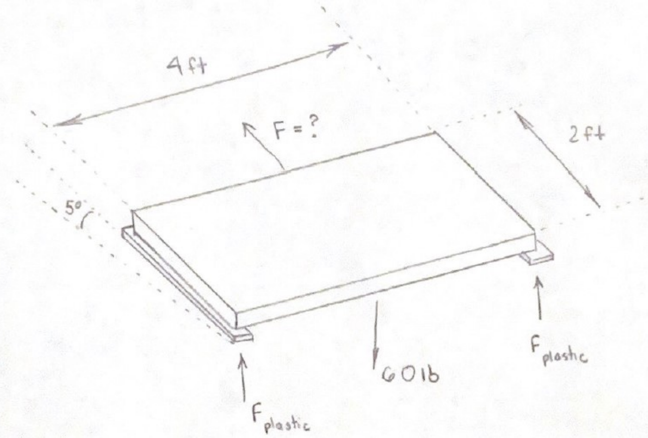
HOME SQ. FOOTAGE — ≈ 250 FT²

TOTAL VOLUME OF WATER — 166.7 FT³

WEIGHT OF WATER (STANDARD GRAVITY) — 166.7 FT³ $\left(\frac{62.4\ lb}{FT^3}\right)$ = 10400 LBS

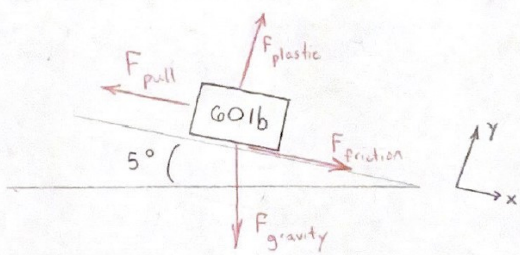
THUS, THE ROOF MUST BE CAPABLE OF HOLDING 10400 LBS, OR 5.2 TONS.

Insulation Panel Force Calcs 1/2



Coefficient of friction for UHMW on dry steel:

$\mu_s = .15 - .2 \quad \mu_d = .10 - .14$



$$\sum F_x = F_{fric} + F_g \sin\theta - F_{pull} = \emptyset$$

$$F_{pull} = F_g \sin\theta + F_p \mu_s$$

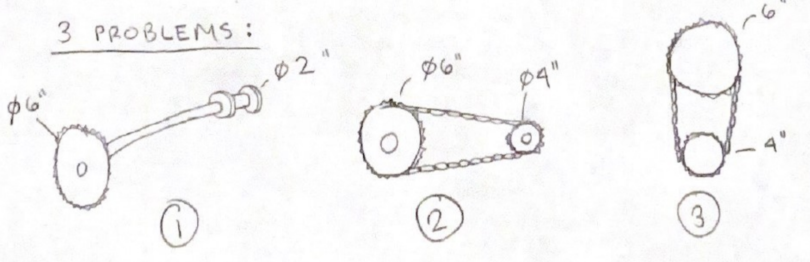
$$= 60\,(lb) \sin 5° + 60\,(0.2)$$

$$F_{pull} = 17.2\ lb$$

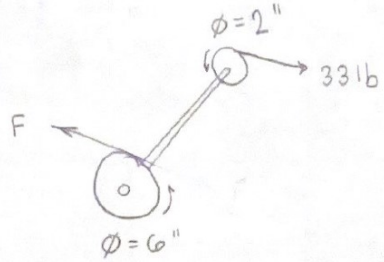
When pulling two panels, force is doubled, so,

$$F_{pull} = 34.5\ lb \leftarrow F_{PULL}$$

3 PROBLEMS:



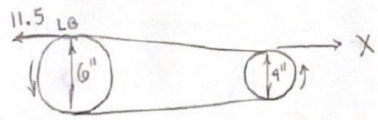
1 INSULATION PANEL FORCE CALCS 2/2



$$\sum M_o = 34.5\,lb(1.5\,IN) - F(6\,IN) = \phi$$

$$F = 11.5\,LB$$

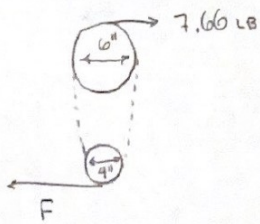
2



$$\frac{11\,LB}{6\,IN} = \frac{X}{4\,IN}$$

$$x = 7.66\,lb$$

3



$$\frac{7.66\,LB}{6\,IN} = \frac{F}{4\,IN}$$

$$\boxed{F = 5.10\,LB}$$

E. Design Hazard Checklist

PDR Design Hazard Checklist **F82 Tiny Home**

Y	N	
X		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	X	2. Can any part of the design undergo high accelerations/decelerations?
X		3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
X		5. Would it be possible for the system to fall under gravity creating injury?
X		6. Will a user be exposed to overhanging weights as part of the design?
	X	7. Will the system have any sharp edges?
	X	8. Will any part of the electrical systems not be grounded?
X		9. Will there be any large batteries or electrical voltage in the system above 40 V?
X		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	X	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
X		15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
X		16. Is it possible for the system to be used in an unsafe manner?
		17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

PDR Design Hazard Checklist **F82 Tiny Home**

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
There will be actuation from the panels on the roof pond, rotating parts for pumps	Cover pinch points with protective material, good seals are required for efficient design		
Roof panels will be large and moving, potentially awning materials	Design with high factors of safety to protect human lives, create physical redundancies to prevent catastrophic failure		
Energy, water systems will likely be mounted on roof of the building, structure could collapse	Design with high factors of safety on structure, design for extreme load cases		
Roof panels and awning will likely be overhanging the side of the house as part of its function	Design with high factors of safety on structure, design		
Solar panels and energy storage may easily exceed 40V	Design according to proper code, insulate and seal electrical systems thoroughly, use warning labels for dangerous voltages and currents		
Batteries for energy storage, pressurized and heated water for personal use	Design according to proper code, insulate and seal electrical and water systems thoroughly, use warning labels for dangerous voltages, currents, and water lines		
Atascadero gets fog, wind, rain	Design for extreme load cases, design according to local building code		
Any creation can be used unsafely	Provide user a list of potentially hazardous features of the design and explain the concept of personal responsibility		

ME 428/429/430 Senior Design Project 2020

DESIGN HAZARD CHECKLIST

Team: F82 Tiny Home Faculty Coach: Sarah Harding

Y	N	
☐	●	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	●	2. Can any part of the design undergo high accelerations/decelerations?
	●	3. Will the system have any large moving masses or large forces?
☐	●	4. Will the system produce a projectile?
●	☐	5. Would it be possible for the system to fall under gravity creating injury?
●	☐	6. Will a user be exposed to overhanging weights as part of the design?
☐	●	7. Will the system have any sharp edges?
☐	●	8. Will any part of the electrical systems not be grounded?
☐	●	9. Will there be any large batteries or electrical voltage in the system above 40 V?
	●	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	●	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	●	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	●	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	●	14. Can the system generate high levels of noise?
☐	●	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
●	☐	16. Is it possible for the system to be used in an unsafe manner?
☐	●	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Figure 4: Design Hazard Checklist, Page 1

Would it be possible for the system to fall under gravity creating injury? Will a user be exposed to overhanging weights as a part of the design?

Yes, our design places a large bladder of water on top of the roof of a small structure. The danger here is that the structure may buckle and fall during an earthquake or other extreme weather, injuring the people inside. The weight of the water on the roof is estimated to be 30 pounds per square foot. There is no way around this as it is a core part of our design. As a result, we designed the structure to be able to support this amount of weight safely. The water bladders can also be drained during a strong storm if necessary.

Is it possible for the system to be used in an unsafe manner?

Since the design is such a large structure, there are inherent risks involved. We will mitigate these with clear labeling. For example, we did not design the insulation panels to be walked on. Usually, everything on a roof is designed to be walked on for ease. But since the panels need to be lightweights to be moveable by hand, they will not be strong enough to walk on. As a result, we will have to put a label on the insulation panels that says not to walk on them.

F. Hand Calculations

SOURCE: ENGINEERING TOOLBOX

USING DESIGN BUILDER,

MAX TEMP (INDOOR) = 89 °F, 33.3°C

MIN TEMP (INDOOR) = 52°F, 11°C

ENERGY NEEDED TO RAISE/LOWER TEMP:

$$q = m c_p \Delta T$$

$m = \rho V$

ρ @ 80°F = 0.0735 $\frac{lbm}{ft^3}$

$V = 15\,ft \cdot 10\,ft \cdot 10\,ft = 1500\ ft^3$

$\Delta T = 92°F - 76°F$ (76°F = high design set point)

c_p @ 80°F = 0.2403 Btu/lbm·F

$$q = (.0735\ \tfrac{lbm}{ft^3})(1500\ ft^3)(.2403\ Btu/lbm \cdot F)(76 - 89°F)$$

$$\boxed{q = -344.41\ Btu}$$

NEEDED TO COOL HOME

$\Delta T = 68 - 52°F$ (68°F = low design set point)

ρ @ 60°F = .07631 lbm/ft³

c_p @ 60°F = 0.2402 Btu/lbm·F

$$q = (.07631\ \tfrac{lbm}{ft^3})(1500\ ft^3)(.2402\ \tfrac{Btu}{lbm \cdot F})(68 - 52°F)$$

$$\boxed{q = 439.91\ Btu}$$

NEEDED TO HEAT HOME

HEAT CAPACITY OF WATER

$1\ Btu/lbm \cdot °F = c_{p\,water @ 70°}$

$(c_p)(\rho)(V)(\Delta T) = q$

$q = 439.91$ Btu

$V = (0.5\text{ ft})(10\text{ ft})(15\text{ ft}) = 75\text{ ft}^3$

ρ @70 $= 62.3\ \text{lbm/ft}^3$

$-344.41\text{ Btu} = (1\ \text{Btu/lbm°F})(62.3\ \frac{\text{lbm}}{\text{ft}^3})(75\text{ ft}^3)\ \Delta T$

$\Delta T = 0.0737$ °F TO COOL
$\Delta T = 0.0941$ °F TO HEAT

MODEL HOME

WATER HEIGHT = 3 IN

ROOF AREA ≅ 5' x 5'

$\boxed{\Delta T = 0.0942\text{°F}}$

G. Initial Intended Bill of Materials (Full systems)

Assembly Level	Part Number	Description	Qty	Cost	Ttl Cost	Source	More Info
		Lvl0 Lvl1 Lvl2 Lvl3					
0	100000	Tiny Home				----	
1	110000	Roof Asembly				----	
2	111000	Solar Panels					
		Solar Panel	1	86.87	86.87	HomeDepot/Grape Solar	Internet #204211365, 100Watts
3	111100	Panel Mounting Parts	1	14.00	14.00	HomeDepot/Grape	Internet #205481382, four Z's with bolts
		Steel Square Tubing	2	0.00	0.00	Found	Needs to be cut to appropriate size
2	112000	Pond Frame			100.87		
2	112100	2"x4"x8'	1	6.85	6.85	Home Depot	Standard Douglas Fir 2x4
2	112101	#9 x 1-1/2" 1/4-Hex Drive Screws	1	9.38	9.38	Home Depot	#9 x 1-1/2 in. 1/4-Hex Drive, Strong-Drive SD Connector Screw (100-Pack)
2	112102	Pond Liner (14.5 mil thick)	1	34.97	34.97	Home Depot	7 ft. x 10 ft. Pond Liner, Reinforced with a strong polyester weave between layers of PVC
2	112103	T50 1/2 in. Leg x 3/8 in. Crown Galvanized Steel Sta	1	3.64	3.64	Home Depot	By Arrow, Model #508
2	112200	Roof Deck			54.84		
2	112201	Roof Asphalt Sealant	1	19.98	19.98	Home Depot	Henry 208R Rubberized Wet Patch Roof Cement Leak Repair – 0.90 Gallon
	112202	36"x36" Aluminum Sheet	2	21.98	43.96	Home Depot	Aluminum Sheet Metal, 0.019" Thick
2	112203	10'x26"x.015" Corrugated Steel Roof	1	22.72	0.00	Found	22 gauge corrugated steel roof 45"x72"
2	112204	#10 1-1/2" Galvinized Hex Screws	1	9.75	9.75	Home Depot	1-1/2 in. Wood Screw #10 Galvanized Hex-Head Roof Accessory (100-Piece/Bag)
2	112205	Gorilla Wood Glue	1	0	0.00	Already Owned	Polyeurethane Wood Glue/Adhesive
2	112300	Pond Cover			73.69		
2	112301	Clear Poly Carbonate Twinwall	2	28.58	57.16	Home Depot	Sunlite 24 in. x 48 in. x 5/16 in. Polycarbonate Clear Twinwall Sheet
2	112302	Waterproof Sealant	1	0.00	0.00	Already Owned	Flex Seal (we already have some -vince)
2	112303	Sheathing Plywood 4'x8"	1	53.45	53.45	Home Depot	Sheathing Plywood (Actual: 0.438 in. x 48 in. X 96 in.), Model #20159
3					110.61		
3							
2	113000	Pond Insulation Panels					
2	113101	- -	1	-	-	-	-
	113102	Polystyrene Foam Insulation	2	34.52	69.04	Home Depot	Rmax Thermasheath 2in 4'x8' R13.1 Insulation board
	113103	Sheet Metal	1	69.00	69.00	B&B Steel Supply	24 Gauge Galvanized Steel Sheet 4ft x 8 ft
	113104	Steel Grabber Plate	1	10.00	10.00	B&B Steel Supply	1/8" steel plate 3" x 48"
	113200	Insulation Panel Tracks			148.04		
	113201	A36 Steel Angle	1	0.00	0.00	Found	1-1/4" x 1-1/4" x 1/8" Steel Angle 10 ft
	113202	UHMW Plastic Strips	5	0.00	0.00	Already Owned	1" x 48" x 1/8" HDPE Plastic
	113300	Insulation Panel Movement System			0.00		
	113301	Wall Mount Flange Bearings	4	11.50	46.00	BearingsDirect.com	1" bore UCF205-16 4-Bolt Flange RCJC-1
	113302	Pedestal Block Bearings	2	11.89	23.78	BearingsDirect.com	1" Pillow Block UCP205-16 Ball Bearing YAS-1
	113303	Steel Pipe	1	10.30	10.30	B&B Steel Supply	A513 Hot rolled tube, 1" OD, 10 feet
	113304	Big Sprocket	1	15.99	15.99	vexrobotics.com	66T Aluminum Plate Sprocket (#25 Chain, 1-1/8" Bearing Bore)
	113305	Small Sprocket	3	11.99	35.97	vexrobotics.com	38T Aluminum Plate Sprocket (#25 Chain, 1-1/8" Bearing Bore)
	113306	Chain	1	11.99	11.99	vexrobotics.com	#25 Standard Roller Chain (10')
		Rope	1	10.00	10.00	Harbor Freight	Thin Weatherproof rope to pull panels
					154.03		
1	114000	Rainwater Collection System					
2	114001	4 in. x 10 ft. White Traditional Vinyl Gutter	1	7.33	7.33	Home Depot	Amerimax Home Products Model #1800700120
2	114002	4 in. White Vinyl End Cap	2	4.40	8.80	Home Depot	Amerimax Home Products Model #T0411
2	114003	4 in. White Vinyl End With Drop	2	8.89	17.78	Home Depot	Amerimax Home Products Model #T0409
2	114004	2 in. White Square Vinyl Downspout	2	11.29	22.58	Home Depot	Amerimax Home Products Model #T0583
2	114005	2 in. x 2 in. White Vinyl Universal Elbow	4	2.39	9.56	Home Depot	Amerimax Home Products Model #T0525
2	114006	Goplus Portable Rain Barrel Water Collector Collap	1	72.98	72.98	Amazon Prime	Collapsible Tank w/Spigot Water Storage Container (100 Gallon)
					139.03		
		Building Structure					
		2x4x8' Boards	18	5.93	106.74	Home Depot	2 in. x 4 in. x 96 in. Prime Whitewood Stud
		2x6x8' Boards	0	9.03	0	Home Depot	not needed
		3/8" 4x8' OSB Board	3	35.98	107.94	Home Depot	3/8 in. x 4 ft. x 8 ft. Oriented Strand Board
		Heavy Duty RigidCasters	2	11.90	23.8	Home Depot	5 in. Gray Fixed plate Caster, 297.7 lb. Load Rating
		Heavy Duty Swivel Casters	2	13.88	27.76	Home Depot	5 in. Red TPU Heavy-Duty Swivel Plate Caster with Brake, 330 lbs. Weight Capacity
		R-15 Insulation	1	42.00	42	Home Depot	R-15 Kraft Faced Fiberglass Insulation Batt 15 in. x 93 in
		#10 Star head construction screws 3"	2	9.50	19	Home Depot	Grip-Rite
					327.24		
Total Parts			**82**		**1108.35**		

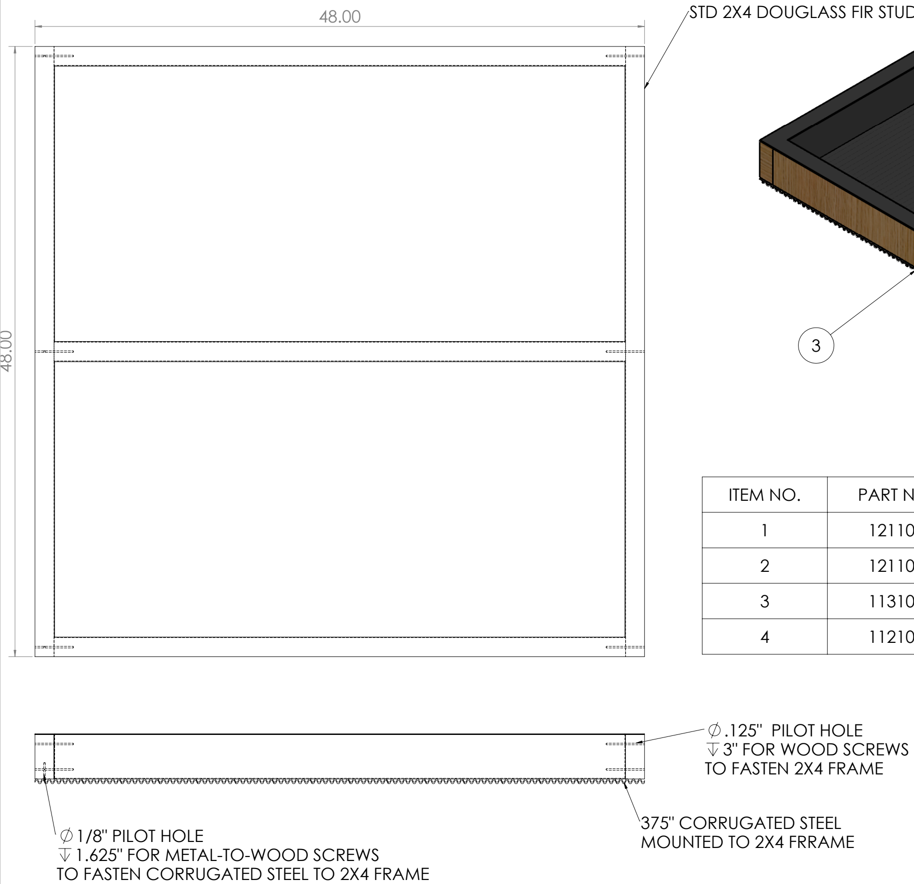
H. Manufacturing Plan Summary Table

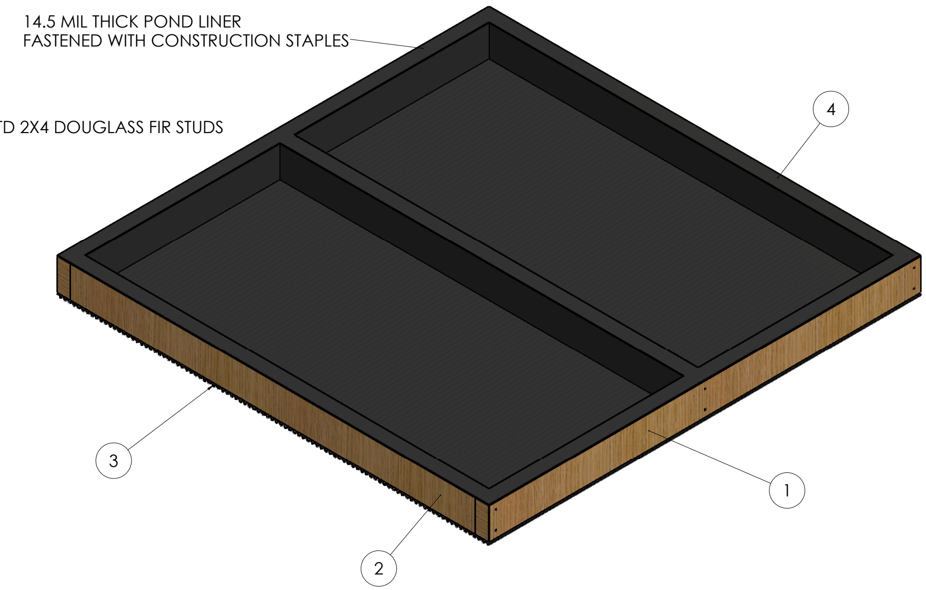
Insulation Panels - Panels	Knife - Score polystyrene insulation board with utility knife, break on line - Wrap foil around panels, secure with 3M spray tack Water Jet - Cut the sheet metal
Insulation Panels – Retraction System	Band Saw - Cut ¾" sch 40 steel tubes to proper length Drill - Drill holes in plywood structure to stick bolts through to secure bearings to structure - Drill holes in A36 steel angle to put screws in it to secure it to the inside of structure
Roof Pond	Saw - Cut frame pieces from wood Drill - Assemble wood frame and drill together - Attach strong ties in critical junctions - Put in water bladders - Mount clear covering over bladders
Tiny Home Base	Table Saw - Cut plywood with table saw
Tiny Home Insulation	Knife - Foam boards must be cut with knife

I. Final Budget Allocation Spreadsheet

Assembly Level	Part Number	Description	Qty	Cost	Ttl Cost	Source	More Info
		Lvl0 Lvl1 Lvl2 Lvl3					
0	100000	Tiny Home					
1	110000	Roof Asembly					
2	111000	Solar Panels					
3	111101	Solar Panel	0	86.87	0	GrapeSolar	Internet #204211365, 100Watts
3	111102	Panel Mounting Parts	0	14.00	0.00	GrapeSolar	Internet #205481382, four Z's with bolts
3	111103	Steel Square Tubing	0	0.00	0.00	Found	Needs to be cut to appropriate size
					0.00		
2	112000	Internal Pond Frame					
3	112101	#8 x 1-1/2" 1/4-Hex Drive Screws	1	9.38	9.38	Home Depot	#8 x 1-1/2 in. 1/4-Hex Drive Connector Screw (100-Pack)
3	112102	Pond Liner (14.5 mil thick)	1	34.97	34.97	Home Depot	7 ft. x 10 ft. Pond Liner, polyester weave between PVC layers
3	112103	T50 1/2 in. Leg x 3/8 in. Steel Staples	1	3.64	3.64	Home Depot	Galvanized staples by Arrow, Model #508
					47.99		
2	113000	Roof Deck					
3	113101	Roof Asphalt Sealant	1	19.98	19.98	Home Depot	Henry 208R Rubberized Wet Patch– 0.90 Gallon
3	113102	10'x26"x.015" Corrugated Steel Roof	0	22.72	0.00	Found	22 gauge corrugated steel roof 45"x72"
3	113103	#8 1-1/2" Galvinized Hex Screws	1	9.75	9.75	Home Depot	1-1/2 in. Wood Screw #8 Galvanized Hex-Head (100-Piece/Bag)
					29.73		
2	114000	Pond Cover					
3	114101	Clear Poly Carbonate Twinwall	1	20.00	20.00	Home Depot	Sunlite 24 in. x 48 in. x 5/16 in. Polycarbonate Clear Twinwall
3	114102	Maple Plywood 4'x8"	1	60.92	60.92	Home Depot	Maple Plywood (Actual: 0.750 in. x 48 in. X 96 in.), Model #20159
3	114103	Steel Roof Pond Cover Frame	60	1.80	108	B&B Steel Supply	60 feet of 1"x1"x0.095" thick steel tube, price $1.80 per foot
					188.92		
2	115000	Pond Insulation Panels					
3	115101	Self-Tapping Sheet Metal Screws	1	6.37	6.37	Home Depot	320 pack 6x1/2" self tapping hex head sheet metal screws
3	115102	Polystyrene Foam Insulation	1	34.52	34.52	Home Depot	Rmax Thermasheath 2in 4'x8' R13.1 Insulation board
3	115103	Sheet Metal	1	91.00	91.00	B&B Steel Supply	24 Gauge Galvanized Steel Sheet 48" x 120"
					131.89		
2	116000	Insulation Panel Tracks					
3	116101	A36 Steel Angle	1	0.00	0.00	Found	1-1/4" x 1-1/4" x 1/8" Steel Angle 10 ft
3	116102	UHMW Plastic Strips	5	0.00	0.00	Already Owned	1" x 48" x 1/8" HDPE Plastic
					0.00		
2	117000	Insulation Panel Movement System					
3	117101	Wall Mount Flange Bearings	4	11.50	46.00	BearingsDirect.com	1" bore UCF205-16 4-Bolt Flange RCJC-1
3	117102	Pedestal Block Bearings	2	11.89	23.78	BearingsDirect.com	1" Pillow Block UCP205-16 Ball Bearing YAS-1
3	117103	Steel Pipe	20	1.05	21.00	B&B Steel Supply	1" OD x 0.065" thick round tubing, $1.05 per foot
3	117104	Big Sprocket	1	15.99	15.99	vexrobotics.com	66T Aluminum Plate Sprocket (#25 Chain, 1-1/8" Bearing Bore)
3	117105	Small Sprocket	3	11.99	35.97	vexrobotics.com	38T Aluminum Plate Sprocket (#25 Chain, 1-1/8" Bearing Bore)
3	117106	Chain	1	11.99	11.99	vexrobotics.com	#25 Standard Roller Chain (10')
3	117107	Rope	1	10.00	0.00	Harbor Freight	Already Owned
3	117108	Spool	2	0.00	0.00	3D printed	3D printed by team member
3	117109	Sprocket Connector	6	0.00	0.00	3D printed	3D printed by team member
3	117110	Hand Crank	1	0.00	0.00	Already owned	Repurposed bicycle crank
					154.73		
2	118000	Rainwater Collection System					
3	118101	4 in. x 10 ft. White Vinyl Gutter	0	7.33	0.00	Home Depot	Amerimax Home Products Model #1800700120
3	118102	4 in. White Vinyl End Cap	0	4.40	0.00	Home Depot	Amerimax Home Products Model #T0411
3	118103	4 in. White Vinyl End With Drop	0	8.89	0.00	Home Depot	Amerimax Home Products Model #T0409
3	118104	2 in. White Square Vinyl Downspout	0	11.29	0.00	Home Depot	Amerimax Home Products Model #T0583
3	118105	2 in. x 2 in. White Vinyl Elbow	0	2.39	0.00	Home Depot	Amerimax Home Products Model #T0525
3	118106	Rain Barrel w/Spigot (100 Gal)	0	72.98	0.00	Amazon Prime	GoPlus Collapsible Tank w/Spigot (100 Gallon)
					0.00		
1	121000	Building Structure					
2	120000	Walls and Floor					
3	121101	2x4x8' Boards	18	6.85	123.3	Home Depot	2 in. x 4 in. x 96 in. Prime Whitewood Stud
3	121102	3/8" 4x8' OSB Board	3	42.93	128.79	Home Depot	3/8 in. x 4 ft. x 8 ft. Oriented Strand Board
3	121103	Heavy Duty RigidCasters	2	11.90	23.8	Home Depot	5 in. Gray Fixed plate Caster, 297.7 lb. Load Rating
3	121104	Heavy Duty Swivel Casters	2	13.88	27.76	Home Depot	5 in. Red TPU Swivel Caster with Brake, 330 lbs. Capacity
3	121105	R-13.1 Insulation	2	34.52	69.04	Home Depot	Pro Select R-Matte Plus-3, 2 in. x 4 ft. x 8 ft. R-13.1 Insulation
3	121106	Door Hinges (pair)	1	3.58	3.58	Home Depot	Hinge, Strap 3" zinc 2 pack
3	121107	Door Latch	1	3.98	3.98	Home Depot	3.5" safety latch
3	121108	#10 Star head construction screws 3"	2	9.20	18.4	Home Depot	Grip-Rite
					398.65		
	Total Parts		**148**		**951.91**	Note: Does not include tax or shipping costs	

J. Drawing Package – Cut plans for wood studs and other





ITEM NO.	PART NO.	PART NAME	DESCRIPTION	QTY.
1	121101	2X4X48	STD. 2X4 DOUGLASS FIR STUD CUT TO 48"	2
2	121101	2X4X45	STD. 2X4 DOUGLASS FIR STUD CUT TO 45"	3
3	113102	CORRUGATED STEEL	.375" THICK CORRUGATED STEEL SHEET	1
4	112102	PONDLINER	14.5 MIL THICK POND LINER	1

NEXT ASSY | USED ON | APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±.05
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

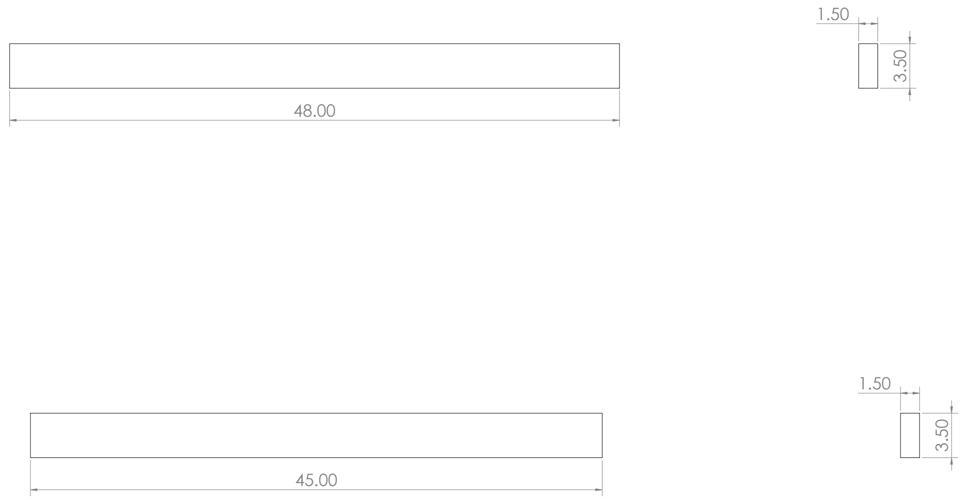
	NAME	DATE
DRAWN	CMG	5/21/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE: INTERNAL POND FRAME

SIZE D | DWG. NO. 112000 | REV

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1



NOTES:
1. MADE FROM STD. 2" X 4" FRAMING STUDS
2. LISTED AS PAT NO. 121101 ON INDENTED BILL OF MATERIALS

NEXT ASSY	USED ON	
APPLICATION		DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±.05
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH

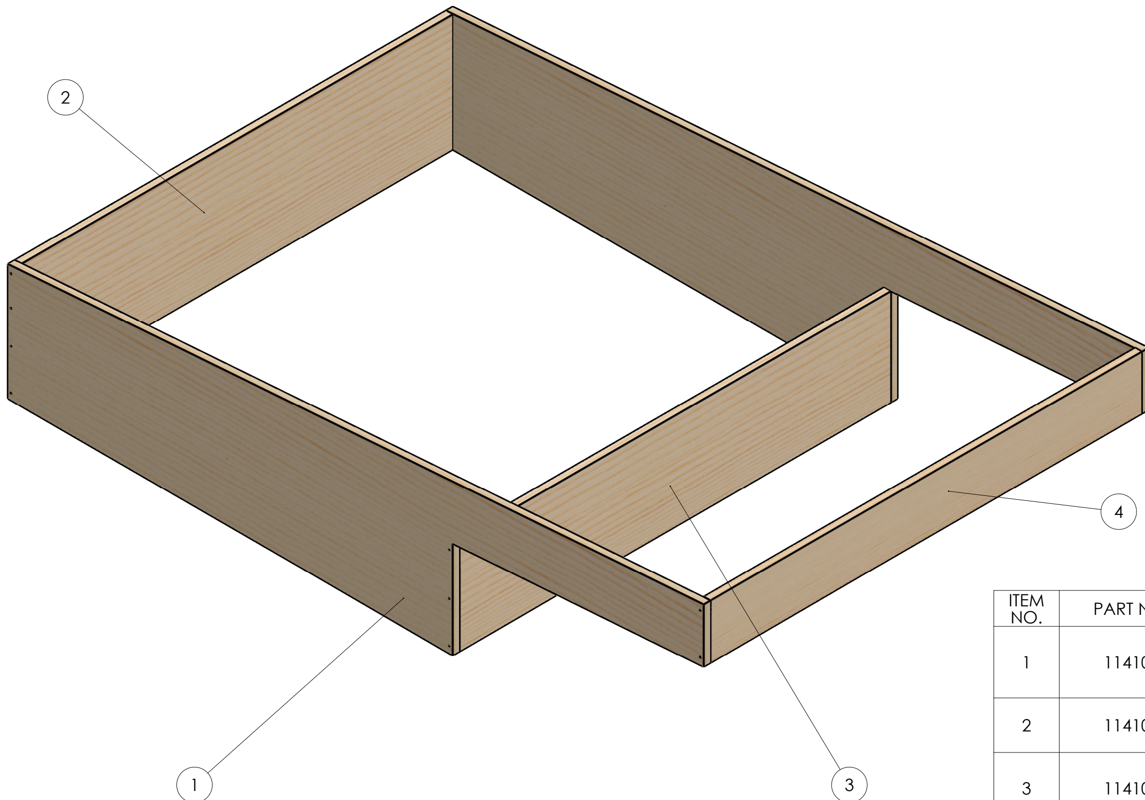
	NAME	DATE
DRAWN	CMG	5/21/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
INTERNAL POND FRAME CUT SHEET

SIZE D | DWG. NO. 112000 | REV

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1



NOTES:
1. OUTER POND FRAMING STRUCTURE IS MADE FROM 3/4" PLYWOOD
2. POLYCARBONATE PANELS AND STEEL ROOF MOUNTING FRAME ARE FASTENED ON TOP OF PLYWOOD COVER
3. SHEETS ARE FASTENED USING #8 1-5/8" WOOD SCREWS EVERY 2-4"
4. DIMENSIONS ARE PROVIDED ON CUTS SHEETS

ITEM NO.	PART NO.	PART NAME	DESCRIPTION	QTY.
1	114102	OUTER FRAME SIDE BOARD	SIDE BOARD THAT RUNS THE LENGTH OF THE ROOF POND SYSTEM	2
2	114102	OUTER FRAME END BOARD - A	END BOARD THAT IS AT THE BOTTOM OT THE ROOF SLOPE	1
3	114102	OUTER FRAME END BOARD - B	END BOARD THAT IS AT THE END OF THE WATER SYSTEM FOR THE ROOF POND	1
4	114102	OUTER FRAME END BOARD - C	END BOARD THAT IS AT THE TOP OF THE ROOF SLOPE	1

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±.05
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

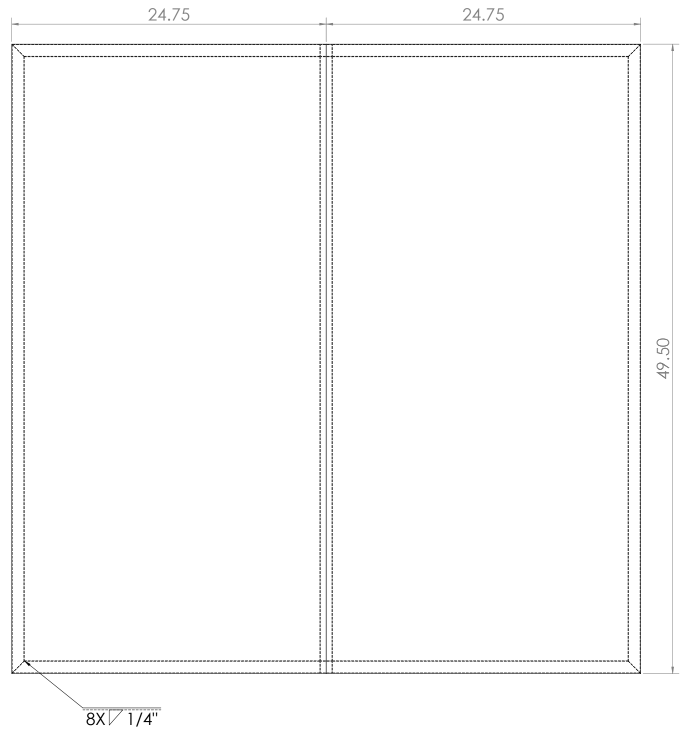
	NAME	DATE
DRAWN	CMG	5/21/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

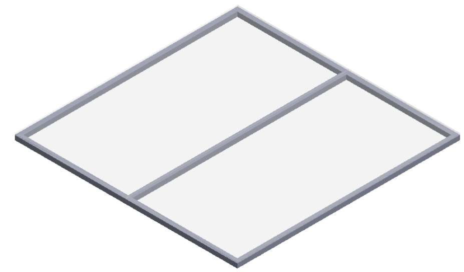
COMMENTS:

TITLE: POND COVER

SIZE D | DWG. NO. 114000 | REV

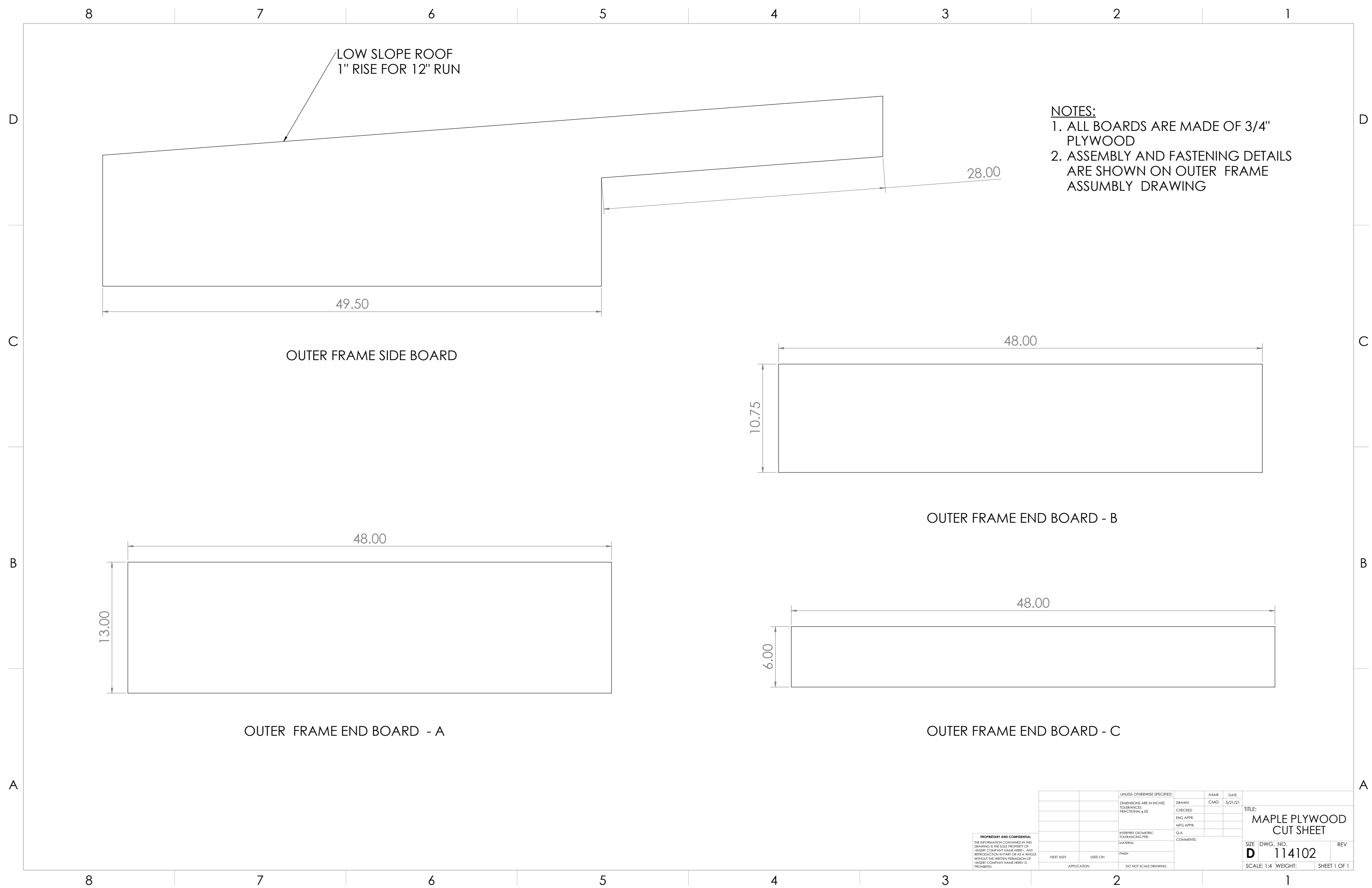
SCALE: 1:4 | WEIGHT: | SHEET 1 OF 2



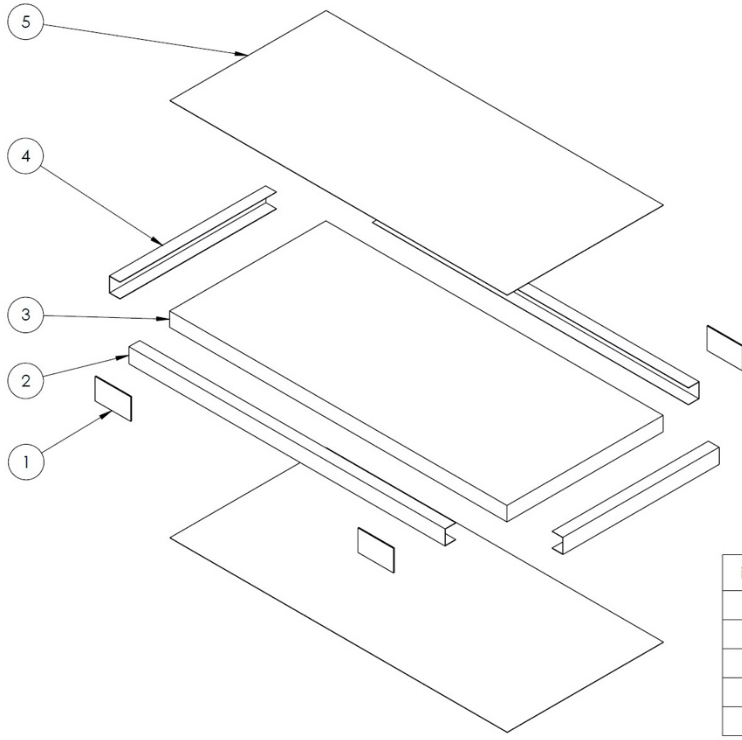


NOTES:
1. STEEL TUBING (PART NO. 114103) AND POLYCARBONATE TWINWALL PANELS (PART NO. 114101) MOUNT TO PLYWOOD POND COVER

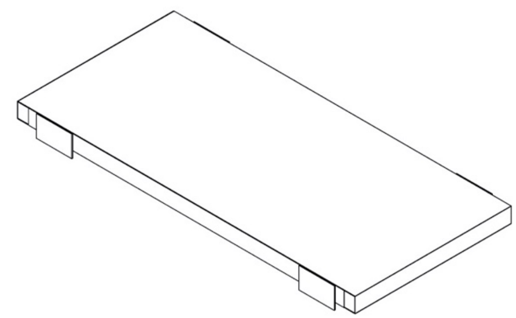
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±.05	DRAWN	CMG	5/21/21	TITLE: POND COVER
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE D DWG. NO. 114000 REV
FINISH				
NEXT ASSY / USED ON / APPLICATION	DO NOT SCALE DRAWING			SCALE: 1:4 WEIGHT: SHEET 2 OF 2



LOW SLOPE ROOF
1" RISE FOR 12" RUN
28.00
49.50
OUTER FRAME SIDE BOARD
NOTES:
1. ALL BOARDS ARE MADE OF 3/4" PLYWOOD
2. ASSEMBLY AND FASTENING DETAILS ARE SHOWN ON OUTER FRAME ASSUMBLY DRAWING
48.00
10.75
OUTER FRAME END BOARD - B
48.00
13.00
OUTER FRAME END BOARD - A
48.00
6.00
OUTER FRAME END BOARD - C
MAPLE PLYWOOD
CUT SHEET
D
114102
SCALE: 1:4
SHEET 1 OF 1



NOTES
1. DRAWING IS IN 1:8 SCALE
2. AFFIX SHEET METAL USING 1/2" SELF-TAPPING SHEET METAL SCREWS EVERY 8 INCHES (NOT SHOWN, PART #115101)



iBOM PART #	DWG PART #	ITEM	DESCRIPTION	QTY.
115103	1	Catch Plate	24 gauge sheet metal 2.25"x6"	4
115103	2	Long Steel Track	24 gauge sheet metal 48"x4" bent	2
115102	3	Insulation Panel	2" Polystyrene hard board 2' x 4'	1
115103	4	Short Steel Track	24 gauge sheet metal 22"x4" bent	2
115103	5	Sheet Metal	24 gauge sheet metal 2'x4'	2

NEXT ASSY | USED ON
APPLICATION

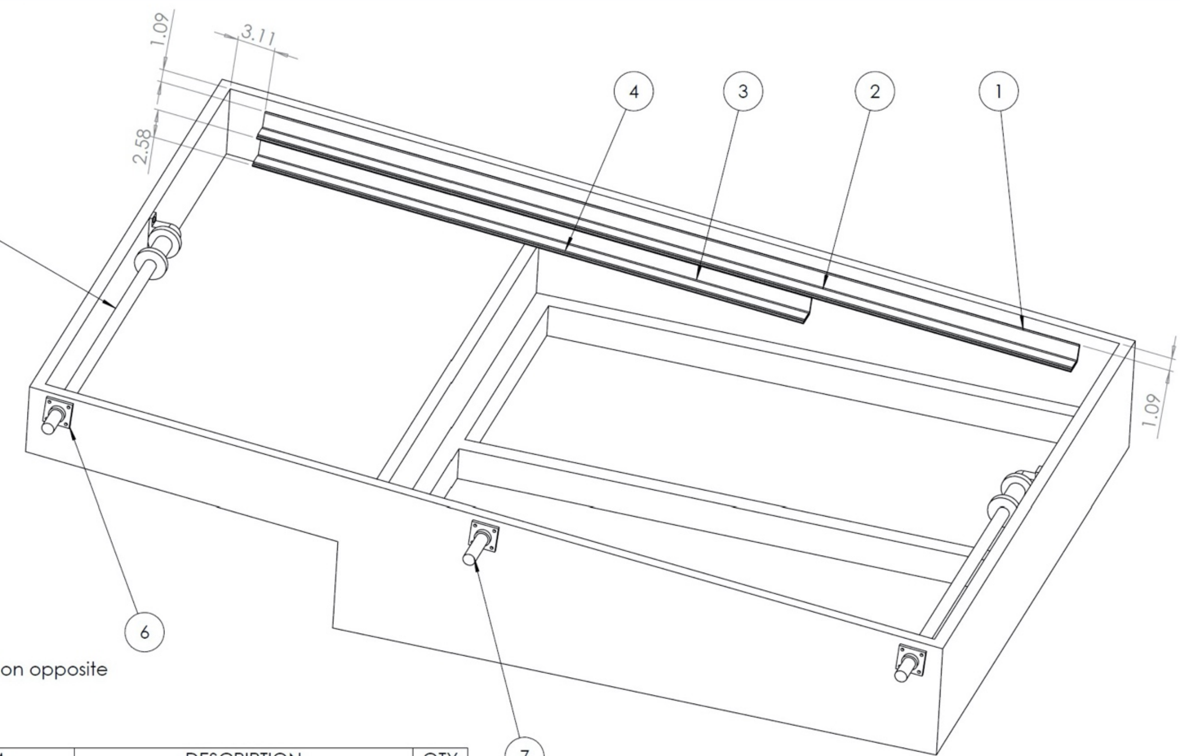
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	VJB	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Insulation Panel Assembly

SIZE B | DWG. NO. 5/10 | REV 2
SCALE: 1:8 | WEIGHT: | SHEET 1 OF 1



NOTES
1. Drawing scale is 1:8
2. Steel angle and strip are mirrored on opposite side hidden by wood frame.

iBOM PART #	DWG PART #	ITEM	DESCRIPTION	QTY
116101	1	Long steel angle	68" long 1.25"x1.25"x0.125" steel	2
116102	2	Long UHMW strip	68"x1"x0.125" UHMW plastic strip	2
116101	3	Short steel angle	46" long 1.25"x1.25"x0.125" steel	2
116102	4	Short UHMW Strip	46"x1"x0.125" UHMW plastic strip	2
117103	5	Long steel pipe	30" long 1" OD steel pipe	2
117102	6	Flange bearing	Wall mount flange bearing 1" ID	4
117103	7	Short steel pipe	8" long 1" OD steel pipe	2

NEXT ASSY | USED ON
APPLICATION

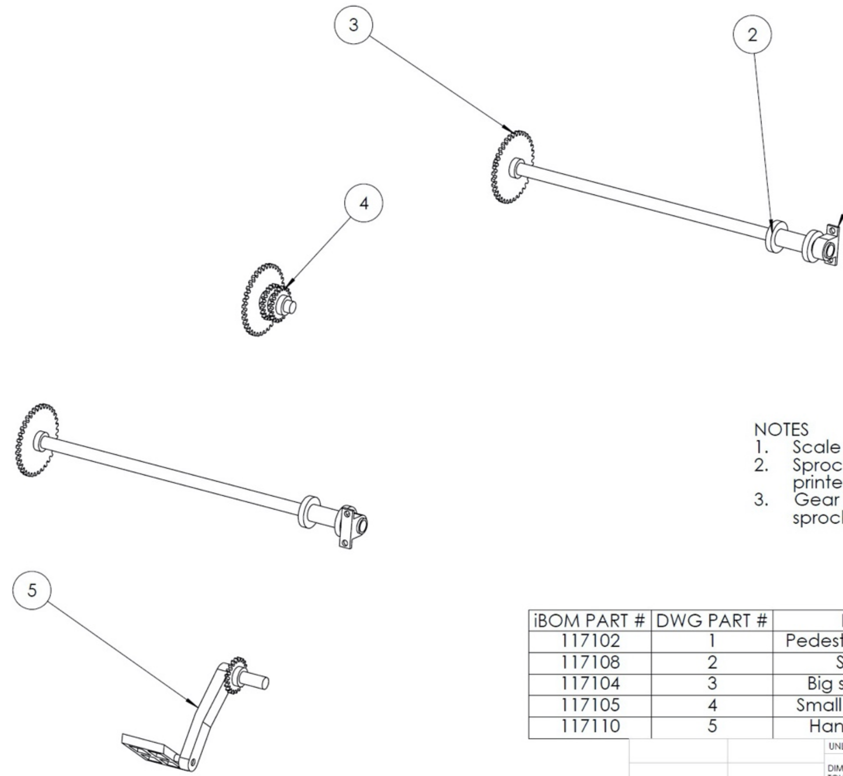
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	VJB	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Steel and UHMW Placement

SIZE B | DWG. NO. 6/10 | REV 2
SCALE: 1:8 | WEIGHT: | SHEET 1 OF 1



NOTES
1. Scale is 1:8
2. Sprockets are connected to pipes with 3D printed sprocket connectors, iBOM part #117109
3. Gear placement is not as important as making sure sprockets are aligned and outside of internal frame

iBOM PART #	DWG PART #	ITEM	DESCRIPTION	QTY
117102	1	Pedestal bearing	1" pillow block ball bearing	2
117108	2	Spool	3D printed rope spool	2
117104	3	Big sprocket	66T Aluminum plate sprocket	3
117105	4	Small Sprocket	38T aluminum plate sprocket	3
117110	5	Hand crank	Reuprposed bicycle crank	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

	NAME	DATE
DRAWN	VJB	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

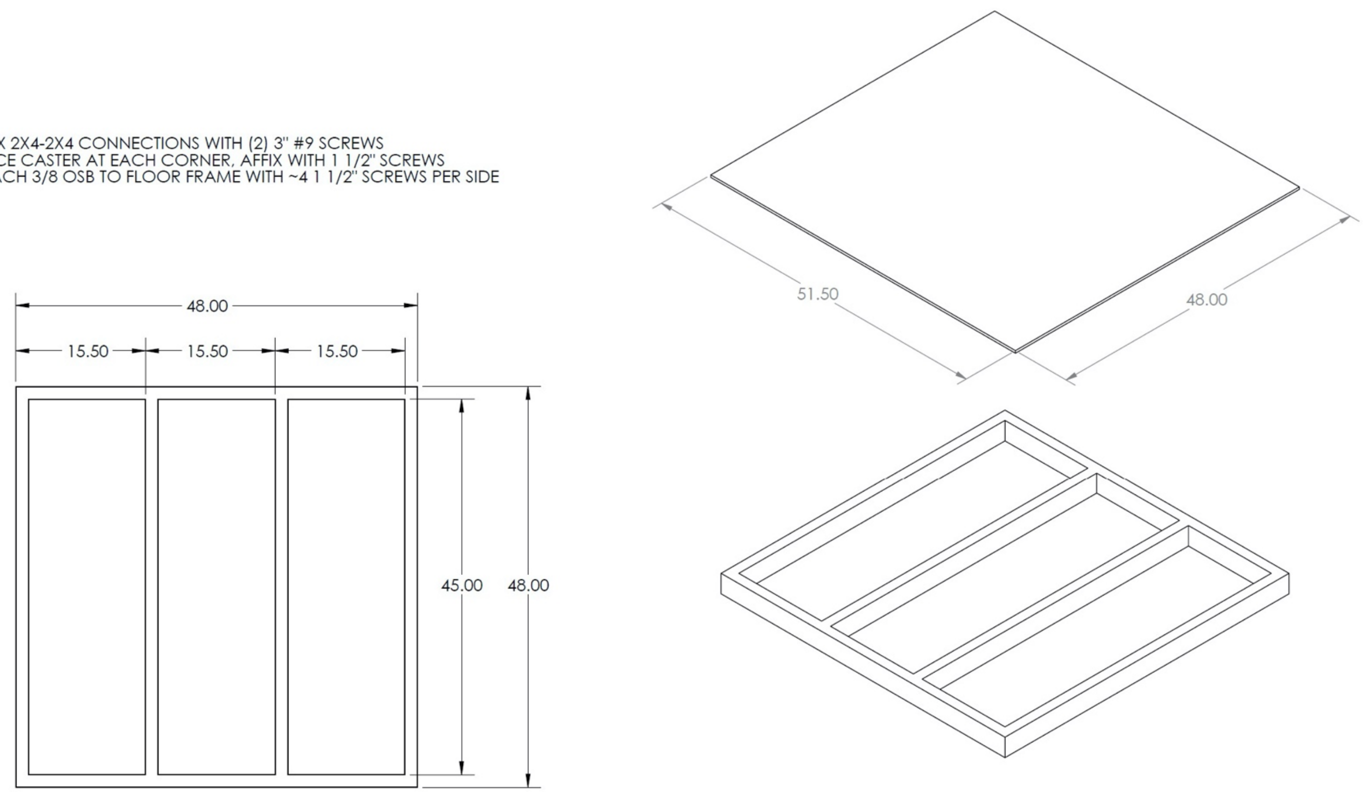
COMMENTS:

TITLE:
Gear Placement

SIZE **B** DWG. NO. 7/10 REV 1

SCALE: 1:8 WEIGHT: SHEET 1 OF 1

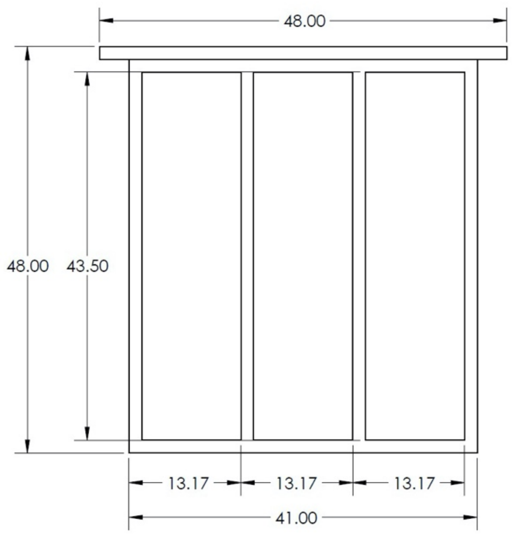
NOTEZ:
1. AFFIX 2X4-2X4 CONNECTIONS WITH (2) 3" #9 SCREWS
2. PLACE CASTER AT EACH CORNER, AFFIX WITH 1 1/2" SCREWS
3. ATTACH 3/8 OSB TO FLOOR FRAME WITH ~4 1 1/2" SCREWS PER SIDE

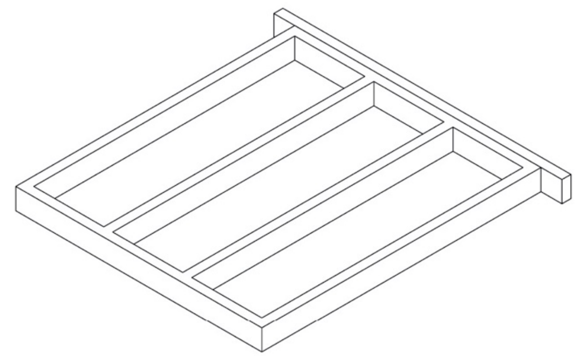


QUANTITY	MATERIAL	LENGTH	DESCRIPTION
4	2X4	45"	
2	2X4	48"	
1	3/8" OSB BOARD	48" X 48"	

Cal Poly Mechanical Engineering	Lab Section: 08	Assignment #	Title: TINY HOUSE FLOOR		Drwn. By: VINCE BUGNI
ME 430 - SPRING 2021	Dwg. #: 7/10	Nxt Asb:	Date:	Scale: 1:12	Chkd. By:

NOTEZ:
1. WE ARE MAKING TWO OF THESE WALLS. QUANTITY LISTED IS TOTAL FOR TWO WALLS.
2. AFFIX 2X4-2X4 CONNECTIONS WITH (2) 3" #9 SCREWS
3. 13.17" ~ 13 3/16"

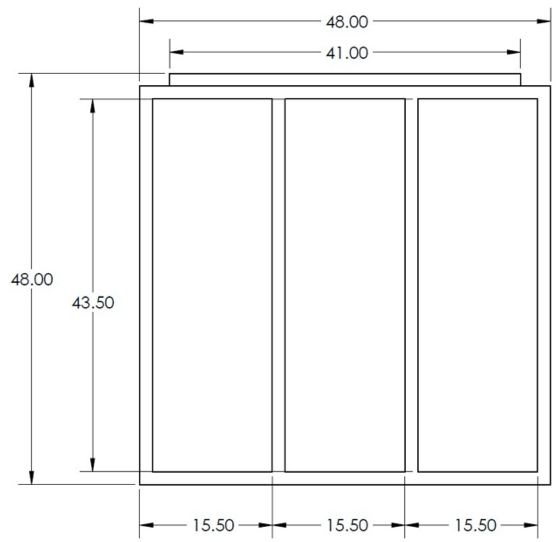


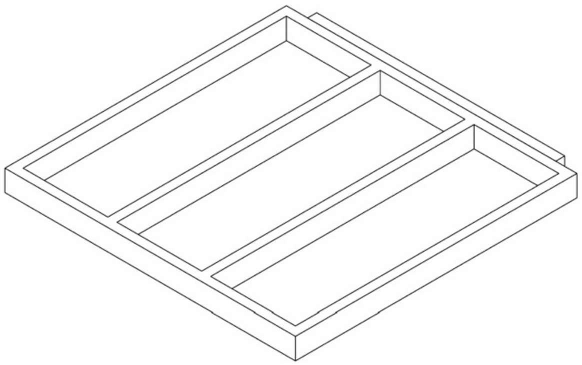


QUANTITY	MATERIAL	LENGTH	DESCRIPTION
8	2X4	43.5"	
4	2X4	41"	
2	2X4	48"	

Cal Poly Mechanical Engineering	Lab Section: 08	Assignment #	Title: TINY HOUSE 4X3.5 WALL		Drwn. By: VINCE BUGNI
ME 430 - SPRING 2021	Dwg. #: 9/10	Nxt Asb:	Date:	Scale: 1:12	Chkd. By:

NOTEZ:
1. WE ARE MAKING TWO OF THESE WALLS. QUANTITY LISTED IS TOTAL FOR TWO WALLS.
2. AFFIX 2X4-2X4 CONNECTIONS WITH (2) 3" #9 SCREWS
3. ATTACH 3/8 OSB TO FLOOR FRAME WITH ~4 1 1/2" SCREWS PER SIDE





QUANTITY	MATERIAL	LENGTH	DESCRIPTION
8	2X4	43.5"	
4	2X4	48"	
2	2X4	41"	

Cal Poly Mechanical Engineering	Lab Section: 08	Assignment #	Title: TINY HOUSE 4X4 WALL		Drwn. By: VINCE BUGNI
ME 430 - SPRING 2021	Dwg. #: 10/10	Nxt Asb:	Date:	Scale: 1:12	Chkd. By:

SOLIDWORKS Educational Product. For Instructional Use Only.

K. User Manual

Tiny Home Passive HVAC

User Manual

Safety Hazards for Operation of Tiny Home HVAC Design

- Gears and chains are not protected or covered from human exposure. Be careful when turning gears, make sure loose clothing and limbs are away from gears.
- There is standing water in the roof of the tiny home. Be careful when moving the tiny home from one spot to the next since the water is not restrained and may spill over. We recommend emptying and refilling the water pond when moving the home.
- Be careful when moving the tiny home to keep feet away from wheels; the tiny home weighs a lot and could hurt if limbs are run over.
- When maneuvering tiny home, be careful not to run it into anything. The home is too tall to see over or around if just being moved by one person; we recommend having at least one person to spot while moving.

How to – Tiny Home HVAC

The tiny home HVAC depends on human interaction to work efficiently. The HVAC is controlled by the insulation panels that cover the water on the roof. These panels can be raised or lowered by a crank on the outside of the home.

Since heating and cooling depends on unpredictable weather, the current tiny home temperature and future days weather should be considered. In the following table, scenarios are described for actions that should be taken in the morning or at night depending on weather and tiny home temperature.

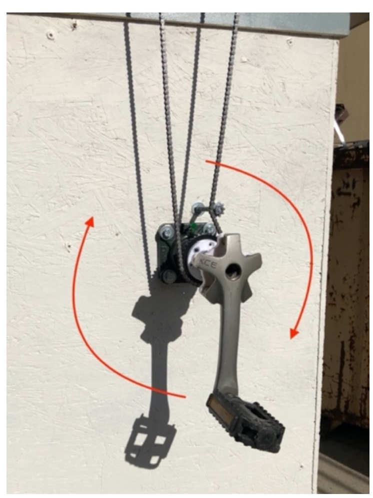
Predicted Outside High Temperature	**Morning Tiny Home Inside Temperature**	**Raise or Lower Insulation**
< 70°F	50 – 70°F	Lower
> 80°F	70°F +	Raise
70 – 80°F	66 – 75°F	Raise – to cool Lower – to heat
Predicted Outside Low Temperature	**Evening/Night Tiny Home Inside Temperature**	**Raise or Lower Insulation**
-	< 68°F	Raise
-	> 72°F	Lower
-	68 – 72°F	Raise – to warm Lower – to cool

As seen in the above table, sometimes arbitrary temperatures can arise. At this point, it is up to the user to decide if they prefer warmer or cooler inside temperatures. The tiny home's insulation panels will only need to be moved (raised or lowered), at most, twice a day, apart from a change of weather in the middle of the day. The following sections will outline the steps to raise or lower the insulation panels. Keep in mind, cooling and heating of the home will be opposite during day and night for constant outdoor temperatures.

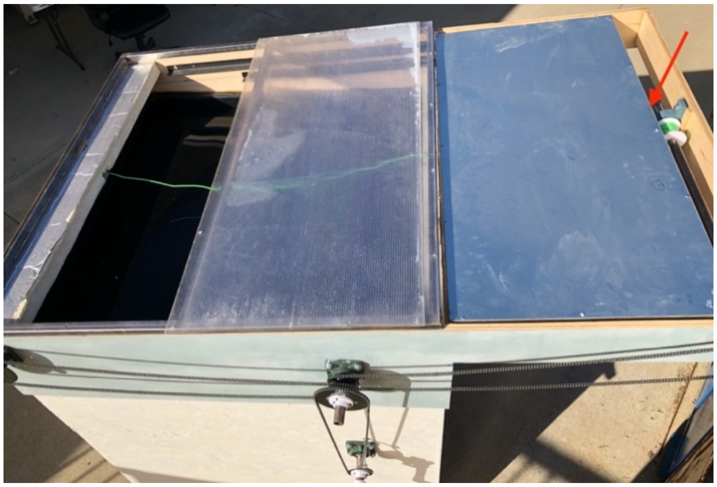
Raise Insulation Panels – Cool Home During Day/Heat Home at Night

To raise the insulation panels, first make sure they are in the lowered position. Find the crank on the outside of the tiny home.

Turn the crank clockwise, you should start to hear the panels moving and feel a slight resistance in the crank.



Continue to turn the crank until you see both insulation panels, together, in the overhang of the tiny home.

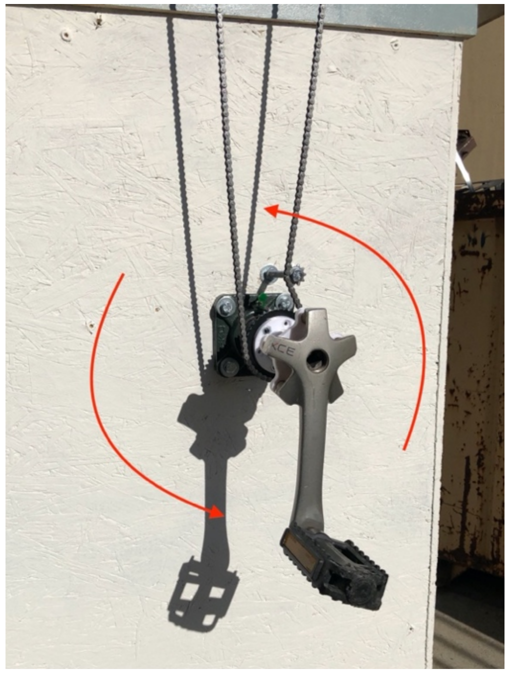


The water should now be exposed to sun radiation during the day, and the home should start to heat up. At night, the water will be exposed to cooler air, and heat will be released from the home.

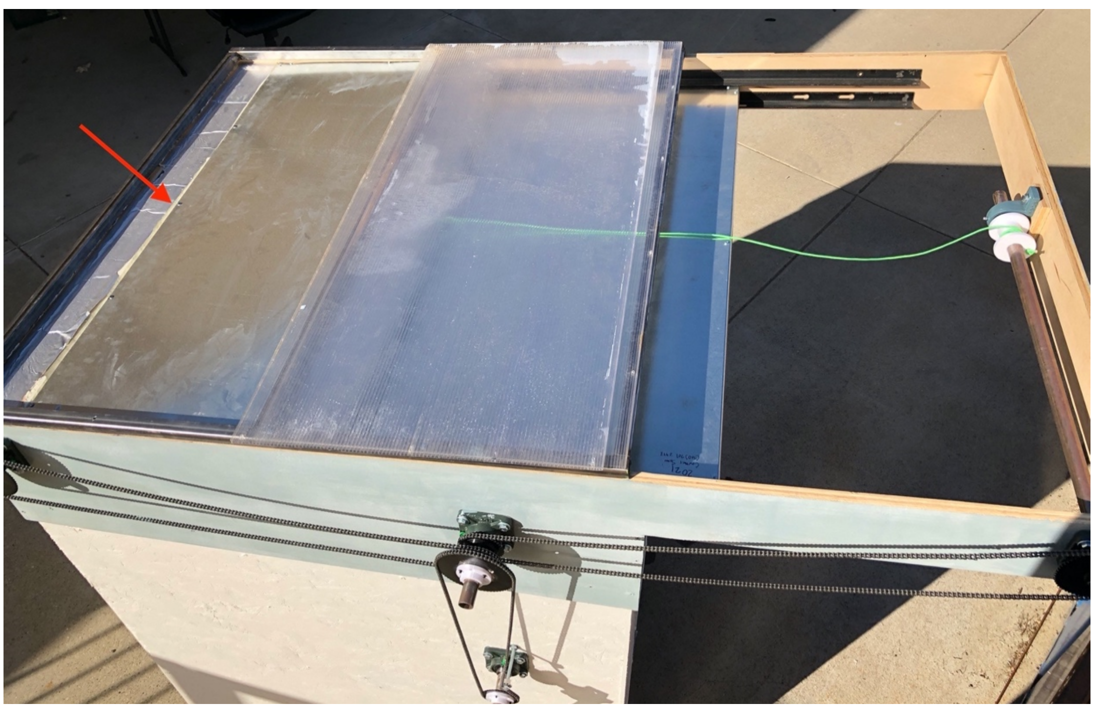
Lower Insulation Panels – Heat Home During Day/Cool Home at Night

Lowering the insulation panels is very similar to raising them. First make sure they are in the raised position. Find the crank on the outside of the tiny home.

Turn the crank counterclockwise, you should start to hear the panels moving and feel a slight resistance in the crank.



Continue to turn the crank until you see both insulation panels, leave the overhang and the top insulation panel reaches the back of the tiny home.



The water should now be protected from the sun's radiation during the day, or protected from cool outdoor temperatures at night, and the home should stay the same temperature.

Replace or Repair

Water Levels: The water in the roof pond is recommended to have a depth of 2-3 inches. The water levels should be checked at least once a week. During periods of high outdoor temperatures, it may be necessary to check the water levels twice a week or more.
Leaks: If the pond liner has any holes or noticeable leaks, immediately remove all water. The water can be easily siphoned out by hose, or a bucket can be used to pail water out. Once the water has been removed, proceed to remove the pond liner by pulling out the construction staples. Inspect the used pond liner to locate the source of the leak along with the potential cause for the tear/hole in the liner. If such a hazard is present, remove it before replacing the old pond liner with a new one. Use new construction staples to secure the new liner.
Insulation Panel Movement System: The sprockets may begin to slip over their axles over time. Simply tighten the set screws using hex keys to ensure the sprockets have enough grip. The chains may begin to squeak and resist movement over time as dirt accumulates. In this event, remove the chains, clean them with a degreasing solution, and apply chain lube.

Replacement Parts List

Item	Source	Use
Douglass Fir Std. 2x4	Home Depot/Local Lumber Yard	Replace any structural/framing damage
#8 x 3" Screws	Home Depot/Local Hardware Store	Used to fasten structural members
#8 x 1-5/8" Screws	Home Depot/Local Hardware Store	Used to fasten plywood sheathing to structural frame
¾" Sheathing Plywood 4'x8'	Home Depot/Local Lumber Yard	Used for Roof Pond external frame
Clear Polycarbonate Twinwall Panels	Home Depot/Amazon	Clear covers for Roof Pond
3/8" OSB Board 4'x8'	Home Depot/Local Lumber Yard	Sheathing for housing structure
Polystyrene Foam Insulation (Rmax Thermasheath 2in)	Home Depot	Insulation for housing structure/insulation panels
UHMW Plastic Strips	Amazon	Allows for Insulation panels to slide with low friction
Wall Mount Flange Bearings (1" bore UCF205-16 4-Bolt Flange RCJC-1)	BearingsDirect.com	For Insulation panel movement system
Pedestal Block Bearings (1" Pillow Block UCP205-16 Ball Bearing YAS-1)	BearingsDirect.com	For Insulation panel movement system
Big Sprocket (66T Aluminum Plate Sprocket (#25 Chain, 1-1/8" Bearing Bore)	Vexrobotics.com	For Insulation panel movement system
Small Sprocket (38T Aluminum Plate Sprocket (#25 Chain, 1-1/8" Bearing Bore)	Vexrobotics.com	For Insulation panel movement system
Chain (#25 Standard Roller Chain (10')	Vexrobotics.com	For Insulation panel movement system
Paracord	Harbor Freight/Local Hardware Store	Cording to pull insulation panels
Gear to Pipe Connectors	3D printer	Connect gears to metal rod with bolts and set screw

L. Testing Procedure – Hot Day

Heat Gain on a Hot Day

Team: F82 Tiny Home
Test Name: Inside Temperature on a Hot Day
Planned Test Date: Week of May 1st (Requires a Full Sunny Day)
Location: Flat Ground in the Sun (Outside of Bonderson, Cal Poly Campus)

Purpose: To determine the viability of the roof pond system as a means of providing adaptable thermal insulation for a small housing unit.

Level of Prototype: Fully Built Structural Verification Prototype
Equipment:

- 1 thermocouple and corresponding manual
- 1 voltmeter

Safety Procedures / Required Personal Protective Equipment:

- None

Data Collection & Documentation

Procedure:

1. Place thermocouple inside the tiny home and connect to the voltmeter.
2. Watch the voltmeter readings change and record the volts once the reading has not changed for one minute.
3. Repeat step two after hold the tip of the thermocouple between fingers until the readings on the voltmeter start to change again.
4. Then place the thermocouple and the voltmeter outside in the shade. Repeat steps 2 and 3.

Set-up to Clean-up Notes:

1. Before beginning the data collection, make sure that the tiny home has been in the sun for at least 24 hours.
2. Make sure that the tiny home has been closed, so that no air has been circulating, changing the inside temperature.
3. The thermocouple must be placed in the center of the tiny home so that it is not touching or close to any walls or the ceiling.
4. During the testing times make sure that the voltmeter and thermocouple are in the shade as solar radiation can cause the readings to be much higher than they really are.
5. To end the test, make sure that the tiny home is secured as before beginning the test and the voltmeter and thermocouple are put away.

Recorded Data:

Temperature	Sunrise	8 am	10 am	12 pm	2 pm	4 pm	Sunset
Inside							

Outside							

M. Testing Procedure – Rainwater Collection

Rainwater Collection Performance

Intent: This test lets our team judge the effectiveness of the rainwater collection system. We have calculated how much water the roof should collect after a measurable amount of rainfall. By comparing the calculated and actual amounts, we can infer how well our roof design works for rainwater collection- a crucial part of a functioning, off(ish)-grid tiny home.
Location: Cal Poly Campus, close to the build site in an open area. Bonderson breezeway or courtyard are possibilities.

Equipment:

- Scale
- Rain Gauge
- Data Collection Chart

Safety Procedures:

- Do not enter structure with water on roof
- Safety goggles and close-toed shoes required

Data Collection & Documentation

Procedure:

1. Place rainwater Collection Tank on scale
2. Tare Scale to show "0" under empty rainwater tank
3. After a period of rainfall, record rainfall amount using rain gauge
4. Read scale to see weight of water
5. Calculate volume of water in tank from observed weight and known density
6. Calculate expected volume of water from roof dimensions and rainfall amount

Set-up to Clean-up Notes:

1. Before beginning the data collection, make sure that the tank is empty, and lines are all connected.
2. Make sure the tiny home and rain gauge are both completely exposed to rainfall.
3. To end the test, make sure that the collection tank and rain gauge are emptied, and the scale removed.

Data:

Rain Guage Reading [in]	Scale Reading [lb]	Amount Collected [in]	Predicted Collection Amount [in]

Recorded measurements are highlighted in blue. The rest of the table requires calculation.

N. Testing Procedure – Building Orientation

Tiny Home Orientation (N, E, S & W)

Location: Cal Poly Campus by Bonderson in direct sun for entire day, in courtyard or parking lot.
Purpose: To evaluate the heat gain of the water due to orientation and the resulting temperature rise inside the home
Equipment:

- 1 thermocouple and corresponding manual
- 1 multimeter
- Fully completed tiny home (no solar or rainwater systems needed)

Safety Procedures:

- Safety issues and responses are not applicable for this test.

Data Collection & Documentation

Procedure:

1. Calibrate thermocouple by connecting it to the multimeter and placing it in boiling water. Use the difference from 212 degrees Fahrenheit for the offset of the thermocouple.
2. Place thermocouple inside the tiny home and connect to the multimeter.
3. Watch the multimeter readings change and record the volts once the reading has not changed for one minute.
4. Repeat step two after hold the tip of the thermocouple between fingers until the readings on the multimeter start to change again.
5. Repeat steps 3 and 4 every two hours from sunrise to sunset.
6. After the sun sets, turn the house 90 degrees. Wait one day.
7. Repeat steps 2-6 – after waiting period is over – for all 3 other orientations.

Set-up and Clean-up Notes:

1. Home must be in full sun throughout the duration of all testing days – includes before and after each test.
2. Make sure the tiny home is fully sealed, so that no air can enter or escape.
3. Ensure the thermocouple is clean and is roughly in the middle of the structure.
4. Store the thermocouple and voltmeter in the shade between readings to eradicate as much error as possible due to harsh solar radiation.

Recorded Data:

	Temperature (F)	Sunrise	8 am	10 am	12 pm	2 pm	4 pm	Sunset
Short wall facing South	Inside							
	Outside							
Short wall facing East	Inside							
	Outside							
Short wall facing North	Inside							
	Outside							
Short wall facing West	Inside							
	Outside							

O. Testing Procedure – Sunny versus Cloudy

Weather Dependent, Temperature Change

Test Name: Inside Temperature Night & Day
Purpose: *To find the 24-hour temperature change inside the tiny home during a sunny and cloudy day*
Scope: Inside the tiny home under the roof pond
Equipment:

- (1) thermocouple
- (1) voltmeter
- Thermocouple manual for conversion constant

Facility: On campus where the tiny home was assembled
Hazards:

- Harm due to roof pond weight overhead when entering the tiny home to place the thermocouple inside. Solve this issue by not putting head inside home, only using arm to briefly place thermocouple.
- No PPE required

Procedure:

1. Place one thermocouple inside the tiny home and connect to one voltmeter. Make sure that the thermocouple is placed in the center of the tiny home and not touching or close to the walls. Also make sure that the voltmeter is not in the sun to eliminate that specific possibility of error in readings. Let thermocouple come to steady state and take data. Then take data again after holding the thermocouple so that it can, again, come to steady state.
2. After step 1, place the thermocouple and voltmeter outside the tiny home, both in the shade.
3. Read and record the voltmeters readings for the required number of times as seen below on data collection table.
4. Using the conversion constant given along with the thermocouple, calculate the temperature.

Collection Schedule	**Testing Scenarios**			
Time	Hot (85°+) sunny day	Hot (85°+) cloudy day	Night after sunny day	Night after cloudy day
Hourly interval testing from sunrise to sunset	X	X		
Hourly interval testing from sunset to midnight. Test again at sunrise.			X	X

Results: The tiny home will pass the tests if the inside temperature stays within the 68 – 76 boundaries. Every testing collection, the thermocouple will be calibrated, and the temperature recorded twice, allowing both times, that the voltmeter and thermocouple come to steady state.
Test Date(s): Specific dates depend on weather, so collection will begin whenever possible from the day after the tiny home model is built.

Test Results:

Temperature	Hot sunny day (°F)	Hot cloudy day (°F)	Night after sunny day (°F)	Night after cloudy day (°F)
Max/Min Inside				
Outside				

Performed By: Because the testing occurs over an 18-hour period, all four team members will take shifts recording the temperature.

Uncertainty Analysis:

Bias Uncertainty – the uncertainty of the thermocouples difference from actual temperature. The thermocouple will be placed in boiling water three times and the voltage will be recorded. After converting the voltage to temperature, the value will be compared to that of 212 degrees F (boiling temperature). This bias value will be determined by first finding the nominal bias:

$$Bias = x_{measured} - x_{referenence} \quad [1]$$

Where $x_{reference}$ is 212 degrees F. After using Equation 1 for all three recorded temperatures, these numbers will be squared, added, and then divided by the number of samples:

$$B = \sqrt{\frac{\sum Bias^2}{n}} \quad [2]$$

Where n is the number of samples, three, and bias is the sum as described before.

Precision Uncertainty – the uncertainty associated with the accuracy of your measurement compared to the actual measurement. This will be found by the resolution of the thermocouple and dividing it by two:

$$P = 0.5 * Res \quad [3]$$

Repeatability Uncertainty – the uncertainty associated with the amount of data taken to the standard deviation of the values. This value will be given by:

$$R = \frac{ts}{\sqrt{n}} \quad [4]$$

Where t is read from Table A.2 for t-values in the ME 236 Course Pack. The values will be read so that 95% are incorporated (alpha = 0.025). s is the standard deviation and n is the number of samples (two).

Error Propagation:

To find the total amount of error in a single temperature reading, the follow equation is used.

$$u_{xm} = \sqrt{(B^2 + P^2 + R^2)} \quad [5]$$

Where B is the bias uncertainty, P is the precision uncertainty, and R is the repeatability uncertainty defined above.

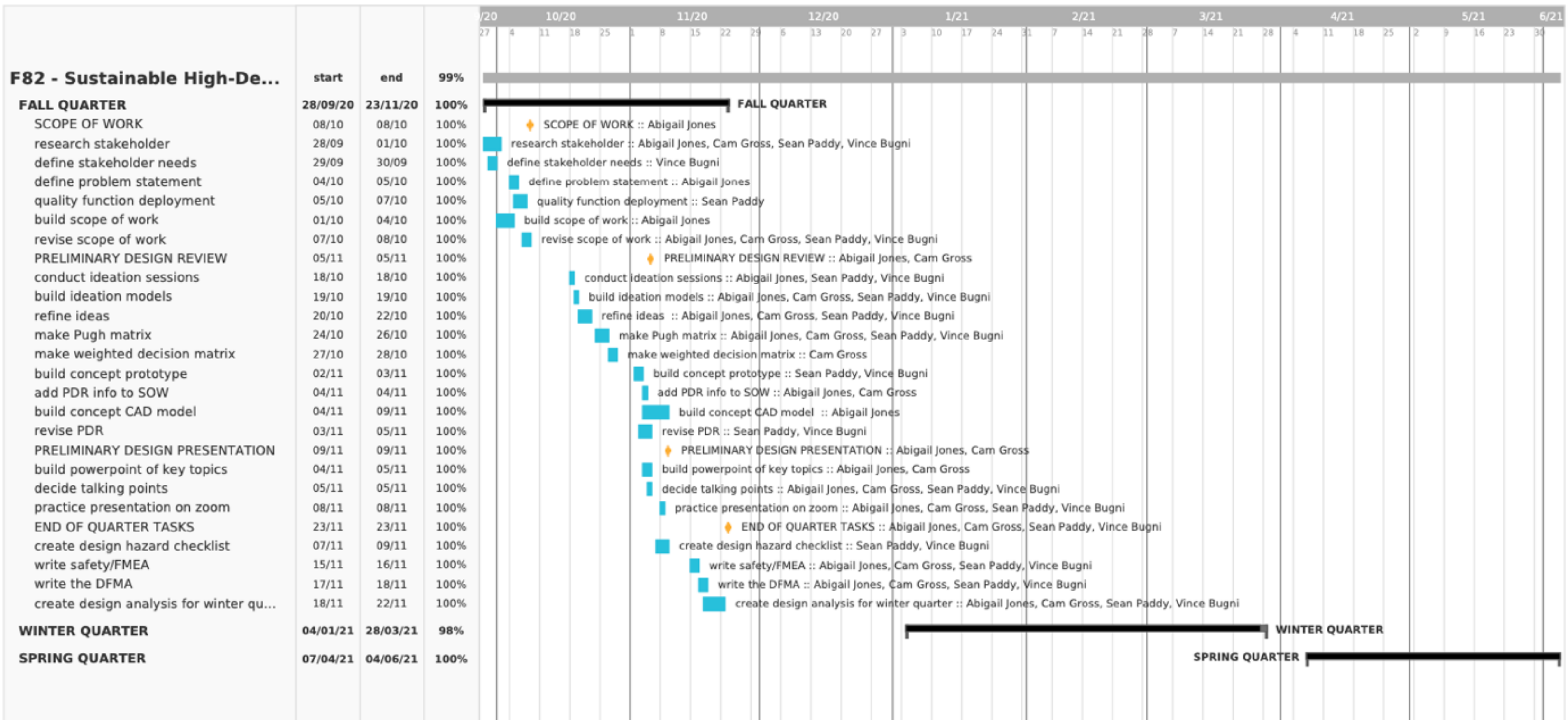
P. Design Verification Plan & Report (DVPR)

Appendix XX.

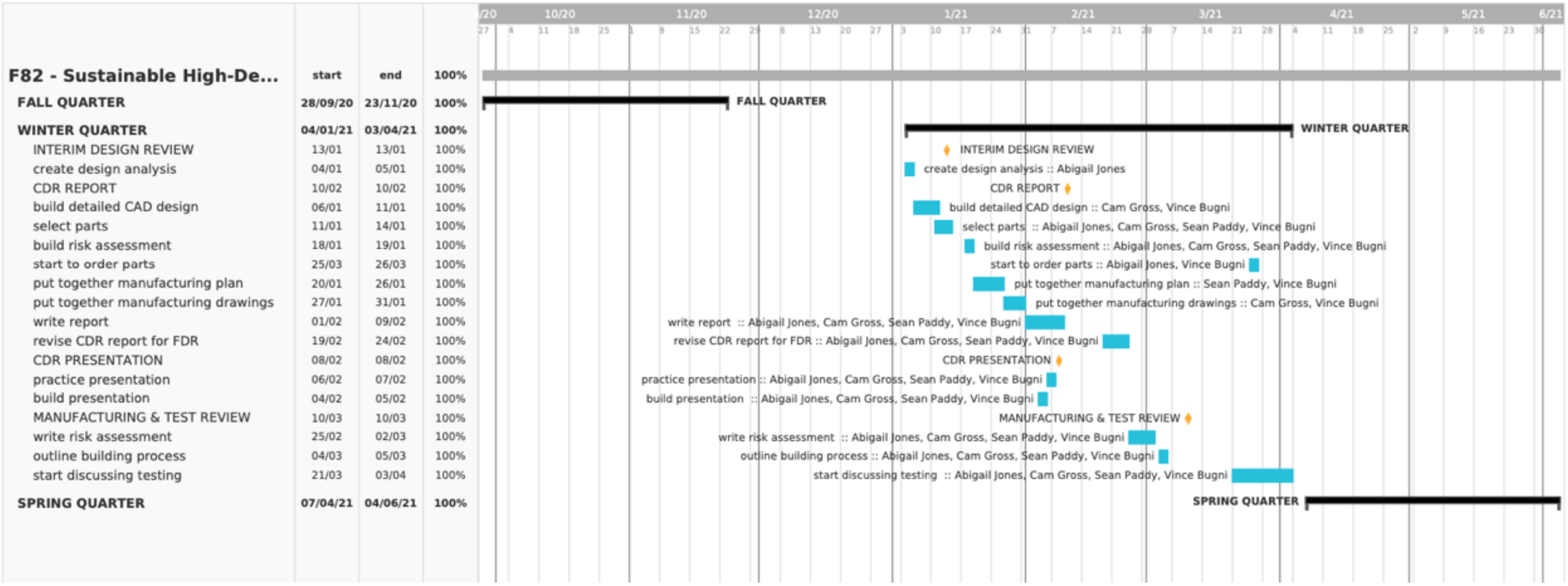
DVP&R - Design Verification Plan (& Report)											
Project:	F82: Tiny Home		Sponsor:		Sarah Harding					Edit Date:	5/19/21
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING		Numerical Results	Notes on Testing
								Start date*	Finish date		
1	Temperature of Tiny Home Relating to Home Orientation	Place the tiny home in sun for a day, measure the temperature. Turn 90 degrees and repeat for four sunny days until all four orientations are finished	Temperature of inside of tiny home	Between 65 and 75 degrees (plus scaling factor)	Outdoor space in full sun, voltmeter	Tiny home	Abby	5/30/2021*	X, wasn't possible, no time	N/A	Also somewhat dependent on location of test.
2	Rain Water Collection	Measure the rainwater guage after a small amount of rain	Measuring rainfall on guage	Amount of rainfall should equal rainwater collected	Outdoor space under rainfall	Tiny home completed with rainwater parts	Sean	5/1/2021*	X, wasn't possible, no rain	N/A	Dry year!
3	Temperature Inside Home	Place tiny home outside during a hot day	Take inside and outside temperature throughout the day	80 Degrees (plus the scaling factor)	Thermometer, outdoor space in sun	Entire tiny home set-up	Cam	5/1/2021*	5/19/21	Avg Temp- 73.5	Continuous testing means that we can track not only the performance of the home across differing sky and temperature conditions, but also get an idea of the system's response to changes in weather.
4	Temperature Inside Home	Place tiny home in an open area where it can be exposed to radiation on a normal temperature (~55-65 degrees) cloudy day	Record the temperature throughout the day	60 Degrees (plus the scaling factor)	Thermometer, outdoor space in sun	Entire tiny home set-up	Vince	5/1/2021*	X, no cloudy days	N/A	
5	Temperature Inside Home	Place tiny home in an open area where it can be exposed to radiation on a normal temperature (~70 degrees) sunny day	Record the temperature throughout the day	60 Degrees (plus the scaling factor)	Thermometer, outdoor space in sun	Entire tiny home set-up	Vince	2/25/2021*	5/19/21	Avg Temp- 64.0	Made sure with this test that the home could be stable in normal temperatures- i.e., doesn't misbehave

***All dates are the same because they depend on weather and we will test accordingly**

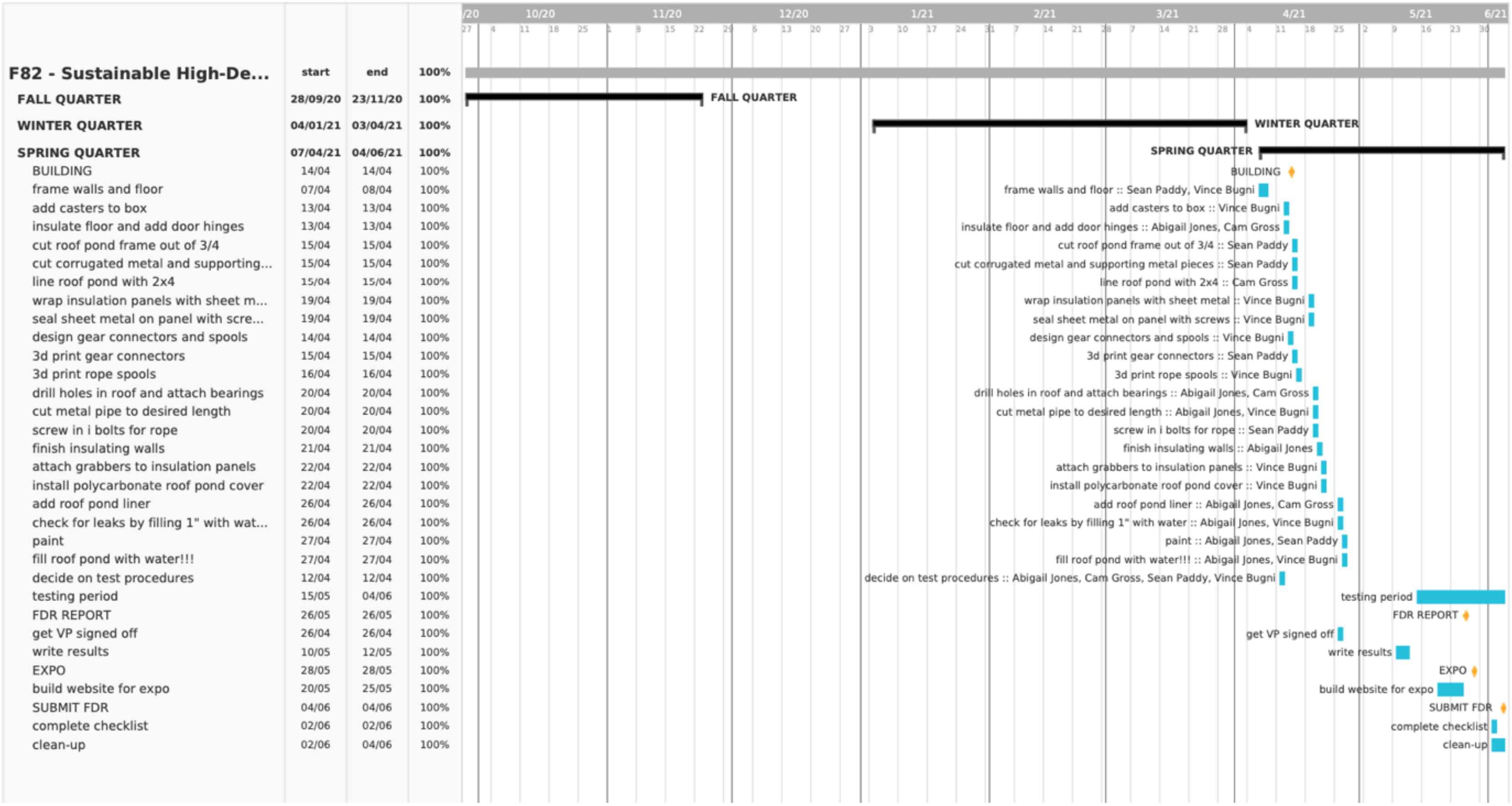
Q. Gantt Chart – Fall Quarter



Q. Gantt Chart – Winter Quarter



Q. Gantt Chart – Spring Quarter



F82 - Sustainable High-De...	start	end	100%
FALL QUARTER	28/09/20	23/11/20	100%
WINTER QUARTER	04/01/21	03/04/21	100%
SPRING QUARTER	07/04/21	04/06/21	100%
BUILDING	14/04	14/04	100%
frame walls and floor	07/04	08/04	100%
add casters to box	13/04	13/04	100%
insulate floor and add door hinges	13/04	13/04	100%
cut roof pond frame out of 3/4	15/04	15/04	100%
cut corrugated metal and supporting...	15/04	15/04	100%
line roof pond with 2x4	15/04	15/04	100%
wrap insulation panels with sheet m...	19/04	19/04	100%
seal sheet metal on panel with scre...	19/04	19/04	100%
design gear connectors and spools	14/04	14/04	100%
3d print gear connectors	15/04	15/04	100%
3d print rope spools	16/04	16/04	100%
drill holes in roof and attach bearings	20/04	20/04	100%
cut metal pipe to desired length	20/04	20/04	100%
screw in i bolts for rope	20/04	20/04	100%
finish insulating walls	21/04	21/04	100%
attach grabbers to insulation panels	22/04	22/04	100%
install polycarbonate roof pond cover	22/04	22/04	100%
add roof pond liner	26/04	26/04	100%
check for leaks by filling 1" with wat...	26/04	26/04	100%
paint	27/04	27/04	100%
fill roof pond with water!!!	27/04	27/04	100%
decide on test procedures	12/04	12/04	100%
testing period	15/05	04/06	100%
FDR REPORT	26/05	26/05	100%
get VP signed off	26/04	26/04	100%
write results	10/05	12/05	100%
EXPO	28/05	28/05	100%
build website for expo	20/05	25/05	100%
SUBMIT FDR	04/06	04/06	100%
complete checklist	02/06	02/06	100%
clean-up	02/06	04/06	100%

R. Risk Assessment

Cause/Failure Mode	Risk Reduction Measures	Severity/Probability
Wires from solar panel to battery storage	All wiring will be insulated, and connections secured before end users interact with the project.	Serious/Remote
Components falling off of roof or roof structure	All fasteners will be fastened to the proper torque specification. All components will be securely fastened to the structure and checked before completion of the project.	Serious/Unlikely
The roof pond movement system requires the user to turn a hand crank, which may require physical exertion.	The movement system's geartrain will feature ratio reductions to reduce the necessary torque input at the crank required to move the panels. This will make turning the crank less strenuous for the end users.	Minor/Likely
The roof pond system could leak water. In the case of catastrophic roof failure, the entire volume of water could fall to the ground.	The pond features a strong liner that will protect against leaks. Furthermore, the pond overflow drain creates a safe routing for small water leaks. The structure of the home will be extremely strong and have a high factor of safety to guard against the possibility of total roof failure.	Catastrophic/Unlikely

Most of these risks involve the building of a livable building of which we are not building. These risks would be taken further into account if large building were to occupy people. The above risks also are included from the most serious of risks associated with our tiny home design concept.

S. Design FMEA

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Severity	Occurence	Criticality
Energy System	Does not provide enough energy	No lighting or electricity	8	Not enough panels, panels loose efficiency over time, wrong placement or orientation, panels are shaded part of the day	Panel efficiecy research, panel size research, placement and orientation research at specific plot of land	2	Solar panel rating and energy demand don't match, energy moniter measures drop-off during times of the day	6	96						
	Energy to home goes out frequently	Hassle for the homeowner	6	Wiring was cheaply made or incorrectly put together, not enough wiring protection against weather and/or animals	Research into solar panel wiring, not taking the cheap way out, analysis of weather effects	2	Wiring has detection system if it fails, wiring is easy to get to for inspection	7	84						
	Intermitent energy	No lighting or electricity during these times	5	Cloudy weather, solar panels are shaded part of the day	Solar energy analysis, latitude and longitude analysis of plot land	5	Energy production is low during days of cloudy weather or parts of the day according to the enrgy moniter	4	100						
	Solar panells/battery are not stable	Solar panels/battery are damaged, could hurt people	9	Bolt/screws were not chosen correctly, framework to home was not considered well, weather and/or animal protected	Structure analysis, FEA stress analysis, weather research of solar panels	2	Monitering of the appearances of the battery and solar panels, cleaning and care of solar panels	8	144						
Rainwater system	System does not collect enough water	more well water must be used to compensate	3	Low rainfall year, clogged or damaged pipes, insufficient tank size	Careful Material choice, backup system design	2	water level monitoring system	7	42						
	system does not retain rainwater	more well water must be used, leaks in tanks	5	Overflow, clogged pipes, collection tank rupture	tank size and strength analysis, robust piping design	4	simple and visible system for easy visual inspection	6	120						
	water quality is compromised	non-potable or potentially harmful water, damage to system	9	Bacteria or comtaminants allowed to grow in system, animals interfering/getting into system, stagnant water	sealed, opaque tanks and pipes, covered openings that prevent contaminats, filters	5	visual inspection, water quality tests	5	225						

Roofpond system - Provides HVAC to Home	Not enough Insulation	Home too cool/hot	6	Insulation panels are too thin, materials wear out, materials are damaged	Heat Transfer Analysis, Research durable materials, case studies	3	Heat Transfer Model, Case Study in Atascadero	5	90	Create a Heat Transfer Model for Analysis					
	Water Evaporates	Home too cool/hot	6	Water container is not sealed, material wears out, materials are damaged	Fluid Vessel Design and Analysis, Test for Air-tight vessel, Heat Transfer Analysis, Add ability to add more water	4	Moniter Water Levels over time	1	24	Create a Heat Transfer Model for Analysis, Create CAD model for fluid analysis, Test a scaled model					
	Dirty Water	Home too cool/hot, health safety	5	Water Container is not sealed, no filtration	Test for Air-tight vessel, Water Filtration Analysis, case study, filter water	4	Moniter water cleanliness over time, test water for presence of bad stimuli	4	80	Create a scale model for filtration testing					
	Roof Pond Collapses	Damage other systems, no roof on the home	10	Not enough structural support, poor material selection, material wears out, materials are damaged	Stress/Structural Analysis, Research durable materials, case studies	2	Structural CAD Model and Stress Failure Theory Calculations	3	60	Create a CAD model for stress analysis, Develop a code for failure theory analysis					
	Water Leaks Out	Home too cool/hot, damage other systems	9	Water container is not sealed, seals are not tight, material wears out, materials are damaged	Test for Air-tight vessel, Stress Analysis, Research durable materials, life cycle analysis, Add ability to add more water	5	Moniter Water Levels over time	1	45	Create a scale model to test sealing methods					
Insulation Panels / insulation	Do not insulate well	The user is too hot or cold	8	1. the panels are too thin 2. the panel material doesn't have insulative properties (R-Value)	1) Look at previous designs 2) perform heat transfer calculations	3	Real life scenario	3	72						
	the panels do not move	a) panels become a hassle to move and thus not as energy efficient b) more than one person required to move panels	8	1) nature debris in guide tracks 2) tracks rust 3) drivetrain of panel movement breaks 4) insulation panels are not sealed and get waterlogged and heavy 5) roller wheels break 6) chain/belt breaks	1) use high quality materials that don't rust 2) shield system from the elements 3) stress analysis 4) monthly system inspection	5	Real life scenario	1	40						
	Get blown off during windstorm	a) flying panels cause human injury	10	1) poor design 2) large windstorm	1) stress analysis 2) fastener shear analysis	1	Real life scenario	1	10						